Vermont Water Resources and Lake Studies Center
Annual Technical Report
FY 2016

Introduction

The Vermont Water Resources and Lake Studies Center (Water Center) facilitates water resources related research and supports faculty and students at Vermont colleges and universities. Research priorities are identified each year, determined by the Water Center Advisory Board, as well as through collaboration with the State of Vermont Department of Environmental Conservation, Lake Champlain Sea Grant, Lake Champlain Basin Program, and other programs in the state. The Director works with state, regional, and national stakeholders to identify opportunities to link science knowledge with decision making in water resource management and policy development. The Director of the Water Center is also the director of Lake Champlain Sea Grant (LCSG) and both programs share the same advisory board, which leverages the strengths of each program. The LCSG currently has limited funds available for research, but is dedicated to research extension through outreach and education. By working closely with LCSG, research extension of the Water Center is enhanced. The Director of the Water Center is also a member of the Steering Committee of Lake Champlain Basin Program (LCBP) and regularly brings information from Center-funded projects to the attention of LCBP committees. His activity on these committees also helps to inform the directions of the Water Center and has led to a number of productive partnerships.

Research Program Introduction

During the 2016-17 project year, the Water Center funded five projects, including four graduate student research projects and one continuing project. Proposals were reviewed by external peers and the advisory board. Water resources management research, including physical, biological, chemical, social science, and engineering were solicited in the RFP. These topics are of interest to stakeholders of the Water Center, including the Vermont Department of Environmental Conservation, the Lake Champlain Basin Program, the Lake Champlain Research Consortium, and Lake Champlain Sea Grant.

The research projects supported by the 104b funds in the 2016-17 project year were:

1. System-wide rapid quantification of streambank erosion, Year 2. Mandar Dewoolkar (School of Engineering, University of Vermont), Jarlath O'Neil-Dunne (Spatial Analysis Laboratory, Rubenstein School of Environment and Natural Resources, University of Vermont), Donna Rizzo (School of Engineering, University of Vermont), Jeff Frolik (School of Engineering, University of Vermont).

2. Quantifying the extent and history of habitat fragmentation in the Lake Champlain basin. Peter Euclide (PhD student, Rubenstein School of Environment and Natural Resources), Ellen Marsden (Rubenstein School of Environment and Natural Resources). Graduate student project.

3. Impacts of climate change on winter-spring transition in plankton communities. Allison Hrycik (PhD student, Rubenstein School of Environment and Natural Resources), Jason Stockwell (Rubenstein School of Environment and Natural Resources). Graduate student project.

4. Can early feeding ameliorate thiamine deficiency in wild lake trout fry? Carrie Kozel (M.Sc. student, Rubenstein School of Environment and Natural Resources), Ellen Marsden (Rubenstein School of Environment and Natural Resources). Graduate student project.

5. Developing high frequency in-situ methods to accurately quantify riverine phosphorus loading to Lake Champlain. Matt Vaughan (PhD student, Rubenstein School of Environment and Natural Resources), Andrew Schroth (Department of Geology), Beverley Wemple (Department of Geography), Andrew Vermilyea (Castleton University). Graduate student project.

System-wide rapid quantification of streambank erosion

Basic Information

Title:	System-wide rapid quantification of streambank erosion
Project Number:	2016VT79B
Start Date:	3/1/2016
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	Vermont-at-Large
Research Category:	Engineering
Focus Category:	Sediments, Models, Geomorphological Processes
Descriptors:	None
Principal Investigators:	Mandar M. Dewoolkar, Jarlath ONeilDunne, Donna Rizzo, Jeff frolik

Publications

There are no publications.

13. Evaluating Quantitative Models of Riverbank Stability

14. Regional or State Water Problem

A growing concern over the past few decades in the Lake Champlain region is the eutrophication of Lake Champlain. The Vermont Agency of Natural Resources identified sediment and phosphorus as the largest contributors to the impairment of surface water quality and aquatic habitat in the State (e.g. VTANR, 2011). Phosphorus has also been identified as the rate-limiting nutrient for the algal blooms in Lake Champlain and has been blamed for accelerating eutrophication for the past several decades (Meals and Budd, 1998). With over 7,000 miles of streams and rivers feeding the Lake, massive amounts of sediment and associated nutrients are discharged each year. High phosphorus levels allow algae to flourish because phosphorus is often the limiting nutrient for growth. Understanding where sediment and its particle-associated nutrients come from is therefore critical for informed and effective land and water management.

Streambank erosion is estimated to account for 30-80% of sediment loading into lakes and waterways (Simon and Rinaldi 2006; Evans, et al. 2006; Fox, et al. 2007). In the Lake Champlain Phosphorus Total Maximum Daily Load (TMDL) report, the Vermont and New York Departments of Environmental Conservation (VTDEC and NYSDEC, respectively), suggested that streambank erosion, such as the example shown in Figure 1, could be one of the most important nonpoint sources of sediment and phosphorus entering streams, rivers, and lakes in the state (VTDEC and NYSDEC, 2002). The Lake Champlain Basin Program (LCBP) also considers streambank erosion to be a potentially important source of phosphorus loading and has advocated the funding of streambank stabilization measures to reduce these loads (Lake Champlain Management Conference, 1996). Langendoen et al. (2012) conducted a study involving extensive field work and BSTEM (Bank Stability and Toe Erosion Model) modeling for the State of Vermont to quantify sediment loadings from streambank erosion in main stem reaches of Missisquoi River. Using the flow records between 1979 and 2010, they predicted that 36% (31,600 t/yr) of the total suspended-sediment load entering Missisquoi Bay was from streambank erosion. These estimates were based on "one-time", yet labor and resource intensive, field work performed at 27 sites that were extrapolated to 110 km of stream length. Although this study demonstrated the feasibility of obtaining estimates of streambank erosion at the watershed level, this approach requires tremendous resources. Also, this method could not provide estimates of deposition; all eroded material was considered to be transported. Here, an alternate approach of using an affordable Unmanned Aircraft System (UAS) is proposed.

Figure 1: Example riverbank failure

15. Statement of Results or Benefits

We propose to assess the capability of the low-cost UAS technology to make reliable quantification of streambank erosion and deposition at variable scales (ranging from site specific to the watershed scale). An UAS can be quickly deployed and acquire continuous images of several kilometers of streambanks, yielding orthorectified imagery and 3D topographic models. Because UAS are not subjected to the high costs and atmospheric constraints of aerial and satellite systems, data can be acquired for a given location at numerous times throughout the year, particularly in early spring and late fall when the vegetation is sparse. Multi-temporal UAS data have the potential to track streambank erosion and stream migration over a desired period of time. This will lead to a reliable and affordable way of quantifying streambank erosion and deposition. The project will capitalize on significant experience developed at UVM in applying UAS and terrestrial LiDAR technologies for characterizing built and natural environments. The proposed study site is Mad River Watershed, which has been one of the major subjects of study under the current NSF EPSCoR RACC research project (http://epscor.w3.uvm.edu/2/node/30). The study area was recently flown for airborne LiDAR by the State; these data will also be useful to the proposed project to some extent. The educational components include graduate and undergraduate researchers and incorporation of research methods and results of this project into UVM courses. Professional development workshops will be developed and conducted for Vermont state and government personnel.

16. Objectives and Timeline

The specific objectives of the study are to:

(1) develop decision support tools to effectively acquire and process continuous streambank profiles using an affordable UAS;

(2) compare the results at select sites from terrestrial LiDAR-based surveys;

(3) develop and validate a methodology to reliably quantify annual system-level streambank erosion and deposition rates; and

(4) develop and incorporate related educational modules for UVM coursework and conduct professional development workshops for Vermont state and government personnel; and prepare and submit manuscripts to journals and relevant conferences.

Our testable hypotheses are summarized in Table 1 below along with the criteria for success.

Table 1 – Research hypotheses

#	Hypothesis	Performance Criterion
1	The UAS-based analysis will yield accurate measurements of streambank changes.	When compared to measurements of streambank changes measured from terrestrial LiDAR the target level of match will be within 10%.
2	UAS streambank mapping will be more cost effective and timely than field survey or terrestrial LiDAR mapping.	A single UAS flight (~40 minutes in duration) will capture 2-8 km of stream and multiple flights will capture at least 10 km of a stream in a single outing. Data processing will be largely automated.
3	UAS streambank mapping will be timely and responsive.	UAS data acquisition will be conducted at key times during the year to coincide with optimal mapping conditions. Following a major event (e.g. flooding) UAS data will be collected within 72 hours. UAS data processing will be largely automated and yield 2D and 3D products within 24 hours of data acquisition.

During the first project year, selection of sites, UAS flights, terrestrial LiDAR scans, and RTK-GPS survey were completed. In Year 2, repeat surveys of all streambank monitoring sites were completed. Initial analysis focused on in-depth comparisons of the UAS and terrestrial LiDAR at select cross-sections. This allowed determination of the baseline reliability and repeatability of UAS data to capture the streambank topography and measure bank movement. Future work in Year 3 will include resurveying the project area under optimal early spring leaf-off conditions in spring 2017 and generation of digital elevation models (DEMs). These will be compared to both aerial LiDAR data from 2013/2014 and earlier UAS data collected during Years 1 and 2 of this project to estimate rates of bank erosion over system-wide scale.

The project builds on the bank stability work we have done under previous Water Center projects, which also laid the foundation for the streambanks related work currently underway for the ongoing National Science Foundation-funded EPSCoR RACC project in the Mad River Valley. The project also benefited from the recent developments of UAS technologies at UVM that are funded by an ongoing U.S. Department of Transportation-funded project on applying UAS imagery for disaster response and recovery.

17. Methods, Procedures, and Facilities

Several methods have been used to quantify streambank erosion and deposition as depicted in Figure 2. One of the most basic methods is direct measurement. For example, Lawler, et al. (1999) made use of longitudinal surveys and pins to quantify sediment loading through bank erosion. Longitudinal surveys allow the measurement of bank top retreat, while the pins allow measurement of toe erosion of laterally migrating streambanks. Direct techniques such as these have been found valuable in determining sediment loads in small watersheds; however, they are very labor intensive. Other approaches have included estimates of lateral channel movements based on the analysis of aerial photography (e.g. Reinfelds, 1997; Hughes, et al., 2006), and more recently, using remote sensing (e.g. aerial or terrestrial LiDAR) observations (e.g. De Rose and Basher, 2011), which are quite expensive.

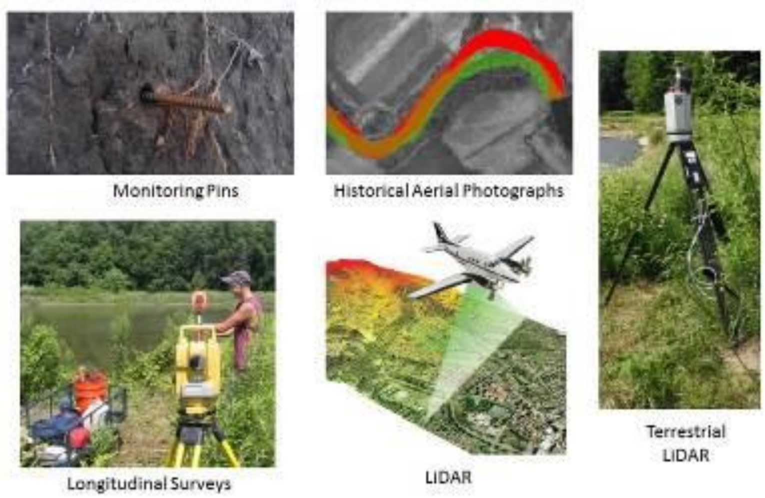

Figure 2: Methods for quantifying streambank retreats

Analytical approaches have used slope stability analysis based on the limit equilibrium method (e.g. Osman and Thorne, 1988; Darby and Thorne, 1996) and often employ computer programs such as SLOPE/W (e.g. Dapporto, et al., 2003; Borg et al., 2014) and BSTEM (e.g. Simon, et al., 2000; Langendoen et al. 2012). The latter model includes fluvial erosion in addition to geotechnical failure. These approaches rely heavily on determination of relevant soil properties and site characterization (e.g. soil classification, unit weights, shear strength parameters, soil suction, root strengths, etc.) requiring extensive field work (e.g. Simon, et al., 2000; Borg, et al. 2014). With the exception of remote sensing applications such as airborne LiDAR, which is expensive; the above mentioned other methods (erosion pins, traditional and terrestrial LiDAR-based surveys, analytical slope stability methods) provide only site specific information requiring crude extrapolations to make watershed-level estimates of streambank erosion. Recent developments in UAS technology provide opportunities to develop methodologies for rapidly and economically determining streambank erosion at system-wide scale. The proposed research employs the following UAS system and terrestrial LiDAR. Both are owned and operated by UVM.

Figure 3. The UAS team preparing for launch of the UAS at Lareau site in Waitsfield

Figure 4. The UAS being launched at Moretown site by graduate student Scott Hamshaw

The UAS to be used for this research is SenseFly eBee, shown in Figures 3 and 4. The eBee is owned and operated by UVM Spatial Analysis Lab (SAL) in collaboration with the Transportation Research Center (TRC). The eBee was purchased under a US Department of Transportation grant. Over 300 flight operations have been conducted yielding over 20TB of 2D and 3D data products. The eBee is lightweight autonomous foam aircraft that contains an integrated 16 MP camera capable of recording aerial imagery at resolutions as fine as 2 cm/pixel. The entirety of this system's hardware can be easily transported in a flight case and rapidly assembled in the field. With a well-practiced team following a set of established standard guidelines, the eBee can be deployed in a few minutes. A field-swappable rechargeable battery provides up to 45 minutes of flight time and allows the eBee to cover areas up to 10 km^2 (3.9 mi^2) in a single flight; and the system can be used in light rain or snow and can tolerate winds as high as 10 m/s (22 mph) (Zylka, 2014). An integrated GPS unit and radio module facilitates communication between the UAS and the associated software (eMotion2) to provide real-time flight monitoring. The stream environment can sometimes be unsafe during storm events and conventional surveying often requires targets to be held in the stream; making UAS a much better alternative.

The terrestrial LiDAR used in this research is a RIEGL VZ1000 model (Figures 4 and 5), which was acquired through a National Science Foundation grant. It is capable of remote three-dimensional mapping of surfaces with very fine resolution (better than 1 cm) that are from 2.5 m to 1,000 m in distance. Each return from the laser pulse system has range and intensity values, as well as spatial position measured in three dimensions. When plotted in 3D space, these returns are referred to as a point cloud. By distributing reflective control targets around an area of interest, it is possible to combine the data collected by several scans at unique locations into a single composite point cloud. UVM also owns copies of the software RiScan and QT-Modeler, which are used to post-process the LiDAR data. The former also allows for multi-station alignment which alleviates the need for specific targets and aligns scans using environmental features. It is to be noted that control targets will not be necessary for the UAS because it is fitted with a GPS unit making it even easier to deploy and use.

A total of about 20 km of stream reaches within the Mad River, New Haven River, and Winooski River watersheds have been selected for this investigation. These include the main stems as well as some tributaries. Seven specific sites within these 20 km stream reaches have been selected for terrestrial LiDAR scans, which cover about 100 m length of the stream at each location. It is anticipated that a total of about eight sets of UAS and companion terrestrial LiDAR datasets would be collected over the 2-year project duration. Data will be gathered in early spring and late fall when the vegetation is sparse; these will total to four sets of data. Two additional data sets will be gathered following significant storm events and also when water levels in the stream are lowest. UAS and terrestrial LiDAR data will be collected concurrently to allow direct comparison and assess the accuracy of UAS-based measurements against the terrestrial LiDAR-based measurements.

The analyzed data will be compared to airborne LiDAR data. The Airborne LiDAR was recently (~May 2014) flown in the Mad River Watershed and the associated data were released in late 2016 (there is usually about a year or longer lag between data collection and dissemination owing to time-consuming data processing and QA/QC). Unfortunately, multi-date airborne LiDAR data will not be available for the study area. Nonetheless, the airborne LiDAR-based data from May 2014 when compared to the UAS and terrestrial LiDAR-based data to be collected as part of this project will allow estimation of streambank retreats between this duration of about a year. This retreat rate could then be qualitatively compared to the ones determined between 2015 and 2016 obtained using UAS and terrestrial LiDAR.

<u>Findings from Year 1 and Year 2 of Project</u>

Data Collection

To-date on this project the UAS was deployed to survey 21 km of river corridor in Central Vermont. Terrestrial laser scanning and GPS surveying were also utilized at 7 detailed streambank monitoring sites. River corridor and stream bank sites are displayed in Figure 6; areas that were surveyed a single time and multiple times with the UAS are identified. Approximately 50% of river corridors were repeat-surveyed at least three times. From spring 2015 to fall 2016, a total of 16 full days of surveying were performed totaling over 50 km (30 mi) of river corridor length.

Figure 5. Mapping area along a section of the Mad River covering the MR-B site for a single flight. Yellow lines are user-selected, pre-programmed flight lines that the UAS follows automatically.

The river corridors were surveyed using an eBee (SenseFly) UAS resulting in the successful acquisition of orthoimagery, true color point clouds, and digital surface models (DSMs). Two models of the eBee were used in this study, the eBee and eBee RTK. The standard eBee UAS was utilized for the first round of flights in late spring (April and May) 2015. Later flights were completed using the eBee RTK which is a survey-grade system that features a more accurate GPS receiver capable of connecting to a virtual or local GPS base station. The UAS imagery was collected at a ground resolution of 3.6 cm with an overlap of 60% to allow for creation of high resolution DSM. An example of the flight path flown by the UAS in a single flight is shown in Figure 5.

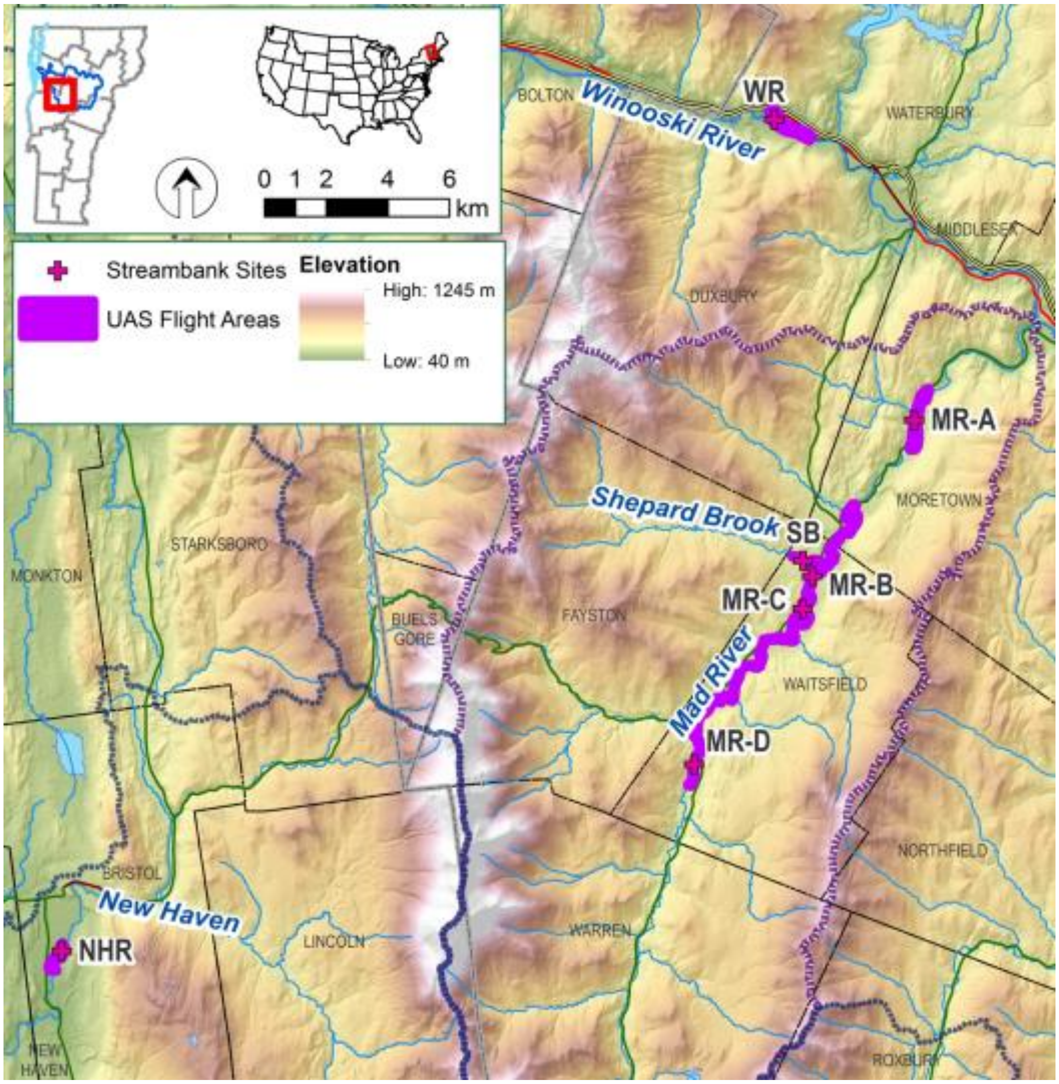

Figure 6. Map of streambank sites for terrestrial LiDAR surveying and areas where data were acquired using UAS.

All areas were flown in early spring, prior to leaf out to minimize the effects of vegetative cover while collecting topographic data. Following a moderate storm event on June 1, 2015, three 1 km reaches were re-surveyed for comparison of pre- and post-storm events. Finally, a 2 km section of the Winooski River in Waterbury was flown and scanned (Figures 7 and 8) in August to assess similar methods on taller streambanks. Repeat surveys of approximately 50% of the river corridor in the Mad River watershed (encompassing streambank sites) were conducted in November after leaf off. An active river reach in Bristol on the New Haven River was also added to the study area and flown in late December. These areas were all resurveyed in spring 2016 again in leaf off conditions. For the entirety of the study area, 2016 was exceptionally dry which resulted in low streamflows and no storms capable of causing bank erosion. Repeat surveys planned for fall 2016 were postponed to spring 2017 to have a greater chance of observing channel change. The one exception to this was a strong late summer storm isolated to the Shepard Brook watershed that caused significant erosion. The Shepard Brook river corridor was therefore resurveyed after the storm to measure bank movement resulting from the storm.

To assess the accuracy and repeatability of the UAS derived topographic data, seven streambank sites were identified for simultaneous data collection using all three methods - UAS, terrestrial LiDAR, and GPS survey. These seven monitoring sites (Figure 6) were selected to represent a variety of bank heights, vegetative conditions, and lateral instability. As summarized in Table 2, bank heights ranged from 1.4 m to 3.7 m and featured different soil types ranging from fine sand to silt loam. Vegetative conditions ranged from no tree cover with only grass to brush and heavy brush and tree cover.

Table 2. Streambank location and characteristics of detailed comparison sites

Site	River	Bank Height	Bank Soil Type	Channel Substrate	Vegetation	Erosion Sensitivity
WR	Winooski	3.7 m	Fine sand	Silt	Grass	High
MR-A	Mad	2.8 m	Fine sandy loam	Silt	Grass / brush	Low
MR-B	Mad	2.2 m	Very fine sandy loam	Gravel	Heavy brush & trees	Medium
MR-C	Mad	2.1 m	Fine sandy loam	Gravel	Heavy brush & trees	Medium
MR-D	Mad	2.0 m	Fine sandy loam	Gravel	Grass / brush	High
SB	Shepard	1.4 m	Silt loam	Gravel	Grass	High
NHR	New Haven	1.9 m	Very fine sandy loam	Gravel	Grass	High

Figure 7. Terrestrial LiDAR data collection along the Winooski River with graduate student Thomas Bryce and undergraduate researchers

Figure 8. Streambank site along Winooski River with active erosion being scanned by the terrestrial LiDAR

Short sections (50 - 100 m) of streambanks were scanned using the Riegl VZ-1000 terrestrial laser scanner to acquire true color point clouds of the bank surface (e.g. Figure 9). A Topcon HiperLite+ RTK GPS System was used to capture a bank profile and ground control points. Table 3 summarizes the timing of data collection at each site. During data collection river flows were not above normal, but sometimes high enough to not be safe for wading and performing ground survey at all sites. Where the TLS and GPS could be utilized safely, ground survey and scans were completed on the same day as UAS flights.

Table 3. Survey dates

SITE	SPRING '15	SUMMER '15	FALL '15	SPRING '16	SUMMER '16
WR	--	8/3/15	--	4/27/16	--
MR-A	5/6/15	--	11/9/15	5/4/16	--
MR-B	4/29/15	--	11/10/15	5/18/16	--
MR-C	4/29/15	--	11/10/15	5/18/16	--
MR-D	4/22/15	6/22/15	11/10/15	5/18/16	--
SB	4/27/15	8/26/15	11/9/15	5/4/16	8/24/16
NHR	--	--	12/22/15	4/27/16	--

Figure 9. MR-A field site on the Mad River showing UAS imagery, area of terrestrial laser scanning, and location of cross section survey with GPS

<u>UAS-derived bank topography accuracy</u>

Analysis to-date has focused on assessing the accuracy of the UAS data through comparison of the UAS, LiDAR, and GPS datasets at the seven streambank sites. To do this, a cross-section approach was used. Point cloud data from both the UAS and LiDAR methods were georeferenced using surveyed ground control points (GCPs) to allow for direct comparison and assessment of accuracy of the UAS data except when using the eBee RTK UAV which is capable of directly georeferencing at high accuracy. Figure 10 shows an example of this raw point cloud data for both survey methods which was compared along selected cross-sections.

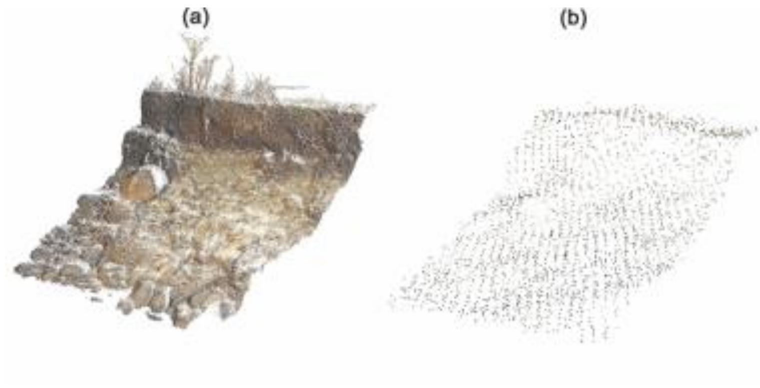

Figure 10. LiDAR (a) and UAS (b) point clouds from the SB site

Because all study sites featured some amount of vegetation, filtering of both the TLS data and UAS data was desired to estimate the bare-earth surface. Two approaches were developed to compare the UAS-derived streambank topography to the TLS and GPS survey: one using a vertical reference plane and the other a horizontal plane. This allowed analysis of the capability of UAS data for both obtaining horizontal bank retreats and for measuring change in ground surface elevation.

The repeatability and reliability of the UAS to capture the streambank topography was analyzed in depth across all seven streambank monitoring sites. Figure 11 shows a bank cross section from two flights flown within an hour of each other. The median difference between the flights was 0.03 m which is approximately equal to the target resolution of the UAS imagery indicating strong agreement in subsequent flights and repeatability in image processing.

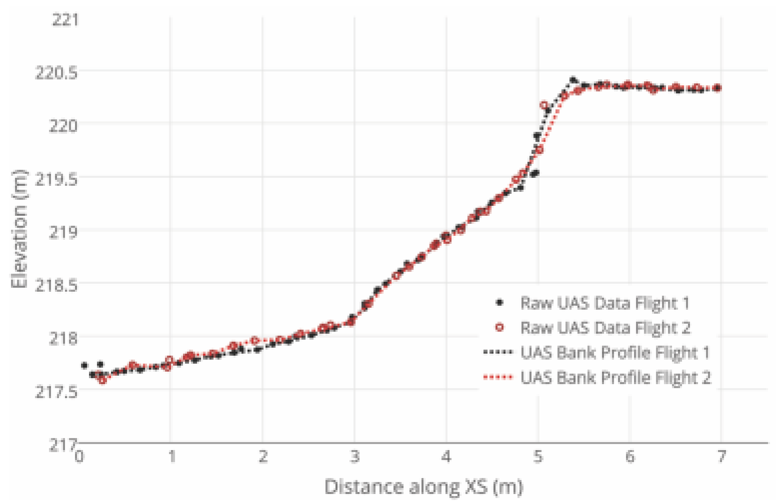

Figure 11. Comparison of data from two UAS flights at streambank site at MR-D site from April 22, 2015, flown within an hour of each other

Using the TLS data as ground truth, the UAS-derived bank topography was analyzed along three cross-sections at each site for all surveys (56 total paired UAS and TLS cross sections). Results showed that the UAS could reliably capture the bank topography under a variety of streambank settings. The overall median vertical error along all the cross sections was 0.11 m. Several trends in the UAS-derived bank profiles were observed. All median errors in UAS data were positive and errors were largest in summer conditions indicating a strong effect of vegetation on the UAS data. This corresponds well to other studies and expectations of a photogrammetry data product. It was also observed that horizontal differences (errors) were larger than vertical ones indicating that care needs to be taken when using UAS data to extract horizontal streambank retreat rates that proper error metrics are calculated.

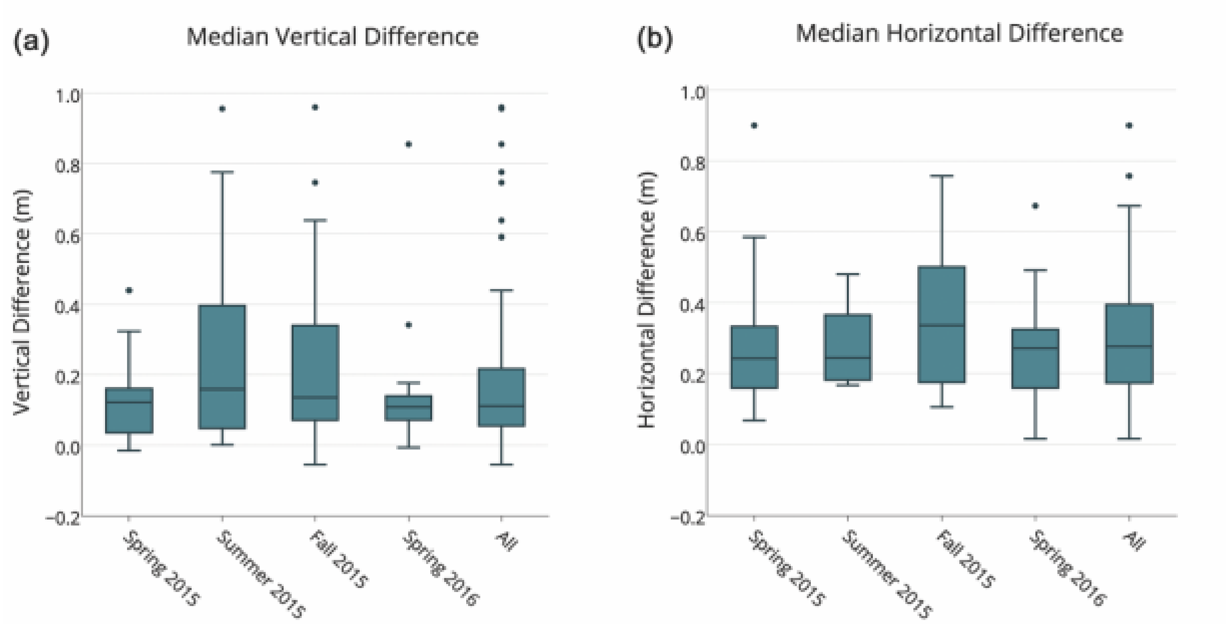

Figure 12. Box plots of (a) median vertical and (b) median horizontal differences between UAS and TLS bank profiles across all sites and cross sections

Change Detection

A snowmelt event on February 26, 2016 caused significant streambank erosion at two locations along the NHR site (Figure 13); cantilever bank failures were observed along the channel resulting in bank retreats up to ~13 m. This event provided an opportunity for direct comparison of bank erosion between the UAS and TLS data at multiple cross-sections. Net change in bank cross-sectional area between the December 2015 and April 2016 surveys were determined for each cross-section. Vegetation conditions on the two dates were very similar allowing for comparison of UAS and TLS to detect change over time.

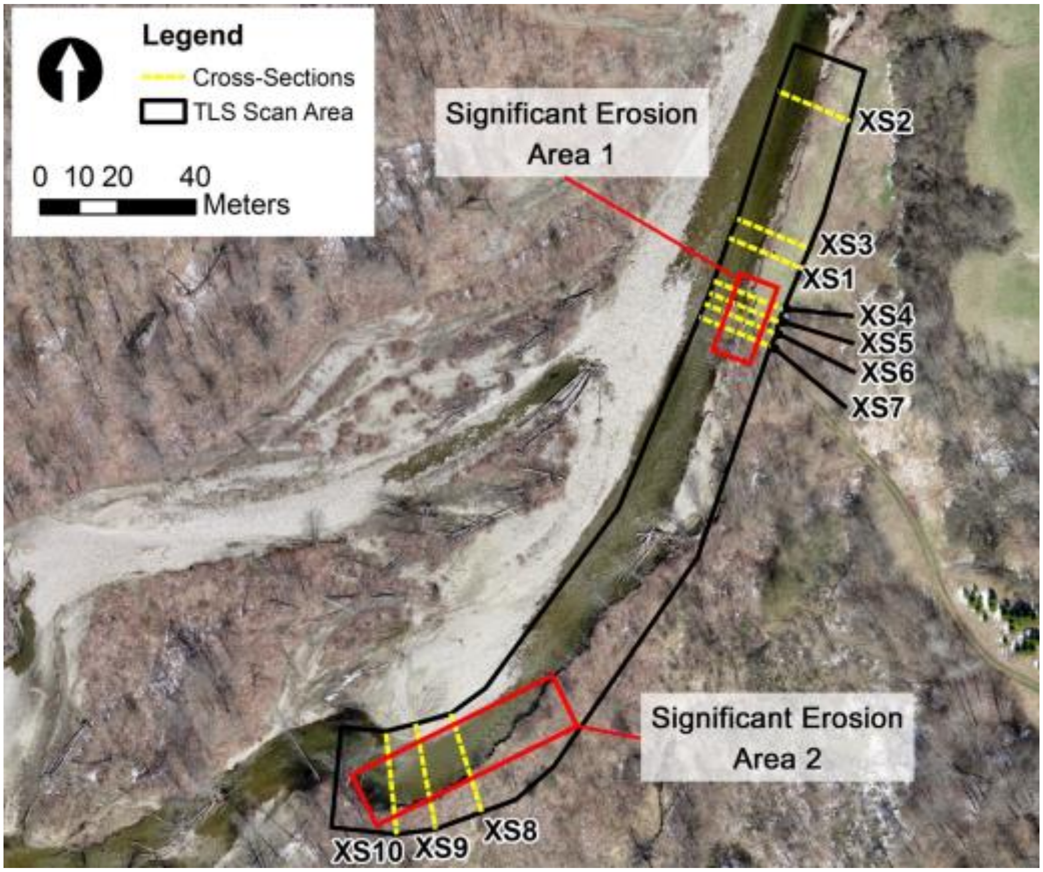

Figure 13. NHR Site with cross sections and area of TLS scan acquisition.

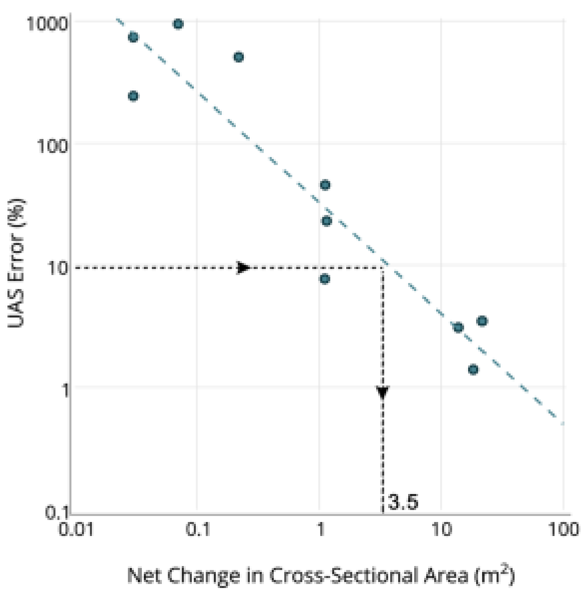

Figure 14. Percent error in UAS measurement of net change in cross sectional area as a function of net change measured by TLS at the NHR site across ten cross sections. Dashed line indicates power law fit of data.

The analysis of the NSH site results indicate that the UAS reliably estimates large amounts of bank movement within 10% of the change captured by TLS surveys along a typical streambank. This error threshold of 10% was observed for net changes in bank cross-section greater than 3.5 m^2 (Figure 14). Translating this threshold to measures of horizontal bank retreat means that for streambanks with typical heights (e.g. 2 m), about 1.8 m of bank retreat provides the 10% level of error, assuming a slab failure. Quantifying erosion or deposition in areas with smaller rates of retreat is more sensitive to the effects of vegetation and other sources of error. An additional source of error is bank under-cutting which creates a challenge for estimating bank erosion amounts using fixed-wing UAS data.

Integration of Research and Education:

So far, four undergraduate students, one MS student, and one PhD student have had direct involvement in the data collection and analysis in this project. Of these, only the PhD student, Scott Hamshaw, was supported by the VT Water Resources and Lake Studies Center grant. The MS student, Thomas Bryce, performed majority of the work for academic credits. The four undergraduate students participated in the fieldwork and research efforts through a variety of summer internships. Two of the undergraduate students (Nathalie Simoes and Wimara Sa Gomes) used VT EPSCoR Research on Adaptation to Climate Change (RACC) summer internships for participating in this research. The other two undergraduate students, Anna Waldron and Kira Kelley, were supported on Richard Barrett Foundation Scholarships. Additional students (PhD student Kristen Underwood, MS student Jordan Duffy, undergraduate intern Alex Morton) were able to participate in some elements of the fieldwork and analysis. The UAS work involved six staff and ten undergraduate students from UVM's Spatial Analysis Laboratory. It is planned that additional undergraduate students will be involved in the project during 2017.

18. Discussion

Data collection and processing workflows and methods were successfully implemented during the first year of the project. This has allowed for analysis of the UAS technology to reliably capture topographic data along streambanks and to be able to detect bank retreat over time. During the 2015-2016 project period, widespread erosion of streambanks did not occur; however, one site (NHR) saw significant bank movement. This allowed for using the NHR site for analysis of change detection in support of testing Hypothesis #1 (Table 1) that suggested UAS-derived surfaces would be able to detect change within 10% of that detected by TLS. It is expected that more extensive erosion has occurred during the 2017 spring melt that will provide more opportunity for evaluating the performance of the UAS for detecting change. Results so far indicate that UAS can reliably estimate bank erosion within 10% of that measured by TLS for banks that experience a net cross-sectional change greater than 3.5 m^2. This was tested on a section of river that featured typical vegetated streambanks. On banks with minimal vegetation, higher accuracies could be expected.

The efficiency of UAS data collection is an important criterion in assessing Hypothesis #2 described in section 16. Single UAS flights performed in the Mad River have covered on average 600 meters of river length and include the entire river corridor with flight times ranging from 25 – 35 minutes. With this length of river covered in a single flight, it was feasible to cover a 5 km reach during a single field outing of about 8 hours. In general, due to suitable landing and take-off locations and visibility of the UAS from the landing/take-off area, two to three flights could be made from a single setup location. This translated to requiring a setup location for approximately each 1.5 - 2 km of river length. While this is less than the proposed performance criteria that Hypothesis #2 hoped, the high ground resolution and overlap did allow for complete data coverage in the area and higher accuracy. Expanding the coverage during a single flight to 2 km would be feasible with a crew that had additional spotters to be deployed upstream or downstream and also if the UAS target ground resolution is reduced allowing flights at higher altitudes. However, currently FAA regulations limit the use of UAS at higher altitudes. During Year 3 of this project, a new model of the eBee UAS (the Plus) that features a longer flight time will be tested.

In support of testing Hypothesis #3, post processing of the UAS data from a single outing in under 24 hours has been successfully accomplished. While some additional filtering or post-processing may be desired, complete coverage of orthoimagery, DSM, DEM, and point cloud are easily completed in under 24 hours. The current requirements for UAS operation have a 72-hour approval process for air space which makes it practical to be on site and collecting data within 72 hours following a major event. There is also a rapid approval process if the situation is time sensitive.

Summary of Planned work for Year 3

Year 3 effort will include repeat flights during early spring conditions prior to leaf-out, with additional flights in response to storm events during summer 2017. Analysis in Year 3 will focus on estimating bank movement over the duration of the project and include comparison to the aerial LiDAR data which are now available. This will allow evaluation of UAS' ability to reliably quantify annual streambank erosion and deposition rates at a watershed level. Additional work is also planned for increasing the efficiency of filtering vegetation from the raw point cloud data to more easily create bare-earth surfaces. Advancements in the UAS imagery processing software will be investigated for this purpose.

Project Leverage of Additional Funding Sources

This project leveraged several additional sources of funding during the first two years. Funding from the U.S. Department of Transportation Office of the Assistant Secretary for Research & Technology provides additional support for UAS operations and processing resources (OASRTRS-14-H-UVM). Funding from the National Science Foundation (NSF) (VT EPSCoR Grant No. EPS-1101317) provides additional support for undergraduate internships and graduate student and faculty support. Additional NSF support through the graduate research fellowship program (Grant No. DGE-0925179) provided additional resources for the full time graduate student on the project. The lead graduate student was also supported from the Department of Civil and Environmental Engineering at UVM for part of the academic year 2016-17. The Robert and Patricia Switzer Foundation provides additional funding support to the lead graduate student on the project. Finally, the Richard Barrett Foundation provides support for undergraduate internships assisting with the project.

19. Training Potential

This research has a strong educational and mentoring component at a variety of levels. A number of graduate and undergraduate researchers have already been engaged in the project and the PIs will continue this effort of integrating research into education. These students are and will gain experience operating UAS and processing UAS data as well as with TLS. That the PIs are from different backgrounds (Civil, Environmental, and Electrical Engineering and Natural Resources), further enriches both the students' experience as well as the potential for the research to make significant gains. The methodology and results have been integrated into educational modules in the CE010 geomatics course at UVM. The data and methodologies will also be integrated into the VermontView Remote Sensing Workshop. This workshop, offered annually at UVM, trains geospatial professionals from federal, state, and local government agencies throughout the state on cutting-edge technologies. The results of this research are being presented at relevant on-campus and off-campus conferences (e.g. AGU 2015, AGU 2016, Geocongress 2017) and will be submitted to proceedings and refereed journals, thus educating a wider group of individuals, researchers and agencies interested in riverbank behavior.

Additional outreach to engage stakeholders and the general public have and will include presentations of the project to different non-profit/community organizations and governmental agencies. To-date these have included presentations to the Vermont Society of Professional Land Surveyors, Vermont Agency of Natural Resources, and members of the Bristol Conservation Commission. A presentation is planned with the Friends of the Mad River organization. Additional offers for presentations will be made to Lake Champlain Basin Program, the Vermont chapter of American Society of Civil Engineers (ASCE), and the Agency of Transportation.

20. Investigators' Qualifications

Mandar Dewoolkar is an Associate Professor in Civil and Environmental Engineering. Through his graduate and post-doctoral research work and industry experience, he has developed significant expertise in the fields of *in situ* and laboratory soil testing, equipment and instrument development and computer-aided slope stability and flow analyses among other types of analytical methods. He has been the PI on two previous Water Center projects.

Jarlath O'Neil-Dunne is the Director of the Spatial Analysis Laboratory (SAL) at the University of Vermont. His research focuses on the application of geospatial technology to a broad range of natural resource issues ranging from water quality to urban ecosystems to land cover change. For the past two years he has served as the principal investigator on a US Department of Transportation grant that pioneered techniques for using unmanned aerial systems to rapidly map and measure transportation and hydrologic networks.

Donna Rizzo is a Professor in Civil and Environmental Engineering. She is a surface and groundwater hydrologist whose research focuses on the development of new computational tools to improve the understanding of human-induced changes on natural systems and the way we make decisions about natural resources. Her involvement using advanced GIS and remote sensing technologies in the above-mentioned research project funded by NSRC in coordination with the USDA Forest Service most closely relates to the proposed work.

Jeff Frolik is an Associate Professor in Electrical Engineering at UVM. His expertise is in sensor networks and he was PI on the NSF Major Research Instrumentation award (CMMI-1229045) that acquired the RIEGL VZ-1000 Terrestrial LiDAR. He has led the use of the terrestrial LiDAR for characterizing a wide range of built and natural environments including streambanks, snow packs, historical structures, and civil infrastructure. In this project, he will train students on the use of the LiDAR system and supervise its use.

Publications and Outreach

Presentations:

Hamshaw, S. D., Dewoolkar, M., Rizzo, D. M., O'Neil-Dunne, J., Rizzo, D.M., Frolik, J., & Engel, T. (2016). *Quantifying streambank erosion: a comparative study using an unmanned aerial system (UAS) and a terrestrial laser scanner.* (Poster), American Geophysical Union 2016 Fall Meeting, San Francisco, California.

Hamshaw, S.D. and Dewoolkar, M. (2016, Oct 4) *Use of unmanned aircraft systems (UAS) to monitor streambank erosion in Vermont.* Presentation to VT Agency of Natural Resources, Montpelier, Vermont.

Hamshaw, S.D. (2016, Jun 10) *Terrestrial Laser Scanning Introduction and Demonstration*. Presentation at Historic Preservation Conference, Waterbury, Vermont

<u>Press and Outreach:</u>

Hamshaw, S.D. (2016, Aug) Interview and filming with Vince Franke for upcoming VT PBS documentary on Lake Champlain.

<u>Education:</u>

Class module on UAS and terrestrial-LiDAR technologies incorporated in to UVM CE010 Geomatics course, Fall 2016 semester

<u>Conference papers and presentations:</u>

Hamshaw, S. D., Bryce, T., Dewoolkar, M., Rizzo, D. M., O'Neil-Dunne, J., Rizzo, D.M., Frolik, J., & Engel, T. *Quantifying streambank erosion using unmanned aerial systems at the site-specific and river network scales*. Geotechnical Frontiers 2017 Conference, Orlando, Florida.

<u>Peer-reviewed manuscripts in progress:</u>

Hamshaw, S. D., Dewoolkar, M., Rizzo, D. M., O'Neil-Dunne, J., Rizzo, D.M., Frolik, J., & Bryce, T. *Quantifying streambank movement and topography using unmanned aircraft system (UAS) photogrammetry with comparison to terrestrial laser scanning (TLS).* Submitted to Rivers Research and Applications, 2017

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Developing high frequency in-situ methods to accurately quantify riverine phosphorus loading to Lake Champlain

Basic Information

Title:	Developing high frequency in-situ methods to accurately quantify riverine phosphorus loading to Lake Champlain
Project Number:	2016VT80B
Start Date:	3/1/2016
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	Vermont-at-Large
Research Category:	Water Quality
Focus Category:	Water Quality, Nutrients, None
Descriptors:	None
Principal Investigators:	Beverley Wemple, Matthew Vaughan, Beverley Wemple, Andrew Vermilyea

Publications

There are no publications.

Project Description

13. Title: Developing high frequency *in-situ* methods to accurately quantify riverine phosphorus loading to Lake Champlain

14. Statement of regional or state water problem

Phosphorus pollution has been identified as a major concern for Lake Champlain by the US Environmental Protection Agency (EPA), which has recently proposed a total maximum daily load (TMDL) for total phosphorus (TP) into the lake (2010). Lake Champlain is a spectacular natural feature and a valuable resource for Vermont that provides drinking water for nearly a quarter of a million people. It offers innumerable recreational opportunities for the region, and is an irreplaceable habitat for wildlife. Millions of state and federal dollars have been invested to curb phosphorus loading into Lake Champlain, though phosphorus levels have not decreased (2015), and storms have been shown to mobilize a disproportionate amount of phosphorus to the lake (Medalie et al., 2012; Smeltzer et al., 2012). A key component of phosphorus reduction plans is monitoring and adaptive management based on efficacy of current approaches. To date, the State of Vermont's methods for monitoring phosphorus pollution have relied on collecting intermittent grab samples for laboratory analysis. This method provides low resolution data, which could misrepresent actual phosphorus loads, especially during storms when concentrations change rapidly and hysteresis effects can introduce significant uncertainty to flow-based estimates. New methods are needed to assess the return on investment gained by state and federal efforts to reduce phosphorus pollution.

Background on phosphorus pollution: Cyanobacteria blooms in Lake Champlain have increased in recent decades, with the most pronounced cases in the shallow bays in the Northeast section of the lake (Smeltzer et al., 2012). In Vermont, phosphorus pollution is a leading cause of these blue-green algae blooms that can release harmful toxins, and eventual eutrophication in these sensitive areas of Lake Champlain. Both recent and historical inputs of excess phosphorus from agricultural and urban areas is transferred to rivers and streams that retain very little phosphorus within the riverine system (Seltzer and Wang, 2000). Export into the lake system then drives phytoplankton growth during the bloom season. Recently, winter and spring storm loading of phosphorus have been shown as important events in terms of phosphorus export (Gerten and Adrian, 2000; Pierson et al., 2013). The magnitude of summer cyanobacteria blooms in Lake Erie have been shown to be positively correlated to spring river discharge and inputs of TP (Michalak et al., 2013; Stumpf et al., 2012).

Accurately characterizing storms is of paramount importance to determine the efficacy of the state's efforts to reduce phosphorus loading. Vermont Agency of Natural Resources has recently reported that although riverine phosphorus concentrations are decreasing, phosphorus concentrations in Lake Champlain have not decreased (2015). This is likely due in part to the effect of legacy phosphorus trapped in lake sediments that can be re-suspended (Sharpley et al., 2013). We hypothesize that this is also due to the increased intensity of storms due to a changing climate. Indeed, we have seen the importance of storms on phosphorus loading in recent years (Gilbert et al., 2014). For example, roughly two thirds of the annual phosphorus load transferred by the Missisquoi River in 2011 was delivered by spring floods, and 9% of the loading occurred during Tropical Storm Irene. In addition, the Winooski River carried more phosphorus to Lake

Champlain in a single day during storm runoff than the annual combined discharges of all 60 of Vermont's wastewater treatment plants in the lake's watershed (2011).

Different land uses are known to disproportionately contribute phosphorus to Lake Champlain. Developed urban and suburban landscapes have a higher percentage of impervious surfaces that do not allow precipitation to infiltrate into the soil, as in a natural or semi-natural system. As a result, discharge rises more sharply in collecting streams, and these higher flows are more likely to erode streambanks, transferring more sediment and phosphorus into Lake Champlain. For example, streambank erosion is estimated to contribute about 36% of TP entering Missisquoi Bay (Langendoen et al., 2012). With this effect combined with phosphorus running off from other human sources in an urban setting, such as parking lots and lawn fertilizers, developed areas account for approximately 16% of the phosphorus loading into Lake Champlain (2015). However, only 2% of the Lake's watershed is residentially or commercially developed (2005).

Agricultural land use contributes an even more significant portion of the lake's phosphorus pollution. While agricultural land use accounts for 12% of the Lake Champlain watershed area (2005), an estimated 38% of the phosphorus entering the lake derives from agricultural activities (2015). Runoff from fertilizers and manure is mobilized to waterways by storms and groundwater flow, and then is transferred to the lake by rivers and streams. Conversely, while 75% of the lake's watershed is covered with forests (2005), this land use contributes only 21% of the phosphorus entering the lake's waters (2015).

Background on phosphorus management and the state's approach: The 2002 phosphorus TMDL implementation and subsequent revisions spanning ten years has defined goals to limit phosphorus pollution into Lake Champlain. In order to reach these goals, Vermont has invested $50 million dollars, and leveraged $52 million of federal funds. The Vermont Agency of Natural Resources has wisely chosen to implement an adaptive management plan, so that the highly variable efficacy of phosphorus reduction practices can be monitored and improved over time. Since the adoption of the phosphorus TMDL plan in 2002, several Vermont agencies have implemented plans to reduce phosphorus loading. These programs have targeted stormwater management systems, back road improvements, wetland protection, streambank stabilization, agricultural best management practices, and green infrastructure development (2010).

To assess the efficacy of these programs, the State of Vermont operates a long-term monitoring program for Lake Champlain along with the USGS and the Lake Champlain Basin Program. Currently, estimates of phosphorus loading are based on intermittent grab samples and flow-based relationships. When precipitation events occur, it is difficult and expensive to deploy personnel to collect samples, especially when storms occur outside of normal hours of operation. Research shows that low frequency (e.g., weekly or monthly) sampling regimes currently in use to monitor phosphorus loading often obscure important high frequency dynamics, and can result in underestimation or overestimation of fluxes (Jeong et al., 2012; Stoddard et al., 2003). TP has been shown to exhibit hysteresis effects and non-linear dynamics with respect to discharge. This makes flow-based correlations difficult or impractical (Schuett and Bowden, 2014). In addition, recent research has shown that large storms can exhibit a threshold condition, where typical flow-based relationships break down (Dhillon and Inamdar, 2013), and sudden stream bank failures can cause large increases in TSS and TP without any appreciable increase in discharge

(Schuett and Bowden, 2014). Direct, *in-situ* observation of phosphorus concentrations at a high frequency (eg. every 15 minutes) would be invaluable to informing Vermont's TMDL goals.

The National Science Foundation funded the development of the Northeast Water Resources Network (NEWRnet) to develop and utilize state of the art water quality sensor technology. This consortium is comprised of research teams in Vermont, Rhode Island, and Delaware and has installed eleven monitoring sites in a variety of land uses. The network focuses on monitoring nutrient dynamics at high frequencies using field rugged optical water quality sensors. This infrastructure and expertise can be leveraged by this project in order to apply newly developed methods to monitoring and managing phosphorus pollution in Vermont.

15. Statement of results or benefits

Currently, phosphorus loading during storms is likely mischaracterized or goes completely undetected by grab sampling methods. The direct benefit of this research will be a novel method that accurately predicts TP and soluble reactive phosphorus (SRP) concentrations in surface waters leading into Lake Champlain at sub-hourly intervals. This will be invaluable to the state's TMDL plans for phosphorus, and will leverage over $100 million in state and federal investments by helping to quantify the effects of management practices. Accurate high frequency data could remove a significant amount of uncertainty from loading estimates, and provide high quality data to base adaptive management efforts. For the first time, managers would have the ability to precisely determine under what condition, to what extent, and for how long tributaries exceed Lake Champlain TMDL thresholds. This would be quite useful for implementing policies and targeted "Best Management Practice" approaches to meet TMDL goals.

In addition, this research will investigate the important differences between phosphorus loading from agricultural, urban, and forested landscapes. It is known that different land uses disproportionately contribute phosphorus pollution to the lake. This research will offer new insights into how the main land uses of the Lake Champlain basin export phosphorus and sediment during storm events and across seasons.

16. Nature, scope, and objectives of the project, including a timeline of activities

This project focused on characterizing watershed-derived phosphorus loading into Lake Champlain by using state of the art *in-situ* water quality sensor technology. Our goal was to develop a method to accurately measure phosphorus concentrations at sub-hourly intervals during baseflow and storms, so that uncertainties in phosphorus loading estimates can be reduced. We developed a calibration algorithm for agricultural, urban and forested land uses and compared the temporal dynamics of phosphorus concentrations among the study watersheds.

This study has the potential to not only improve load estimates for TP, but also parse out fluxes of different phosphorus species. While previous estimates of phosphorus loads have focused solely on the relationship of TP with TSS, our equipment is capable of creating a richer relationship that would include dissolved phosphorus species in addition to TP. With a single measurement, the absorbance spectrophotometer measures absorbance in the full UV-Visible (UV-Vis) spectrum. Although phosphorus species are not known to absorb light in this spectrum, preliminary results indicate that watershed properties cause other detectable dissolved constituents to correlate well with SRP, resulting in a functional relationship.

While funding will be utilized for one year, the benefit of this funding will span multiple years of data. New methods and calibration algorithms can be retroactively applied to existing sub-hourly absorbance and nephelometric data that has already been collected at the NEWRnet sites across the state of Vermont, and can be applied to future monitoring observations.

Objectives

1. Develop method to determine phosphorus concentrations based on UV-Vis absorbance spectra, and nephelometric measurements
2. Determine the differences in TP and SRP calibration algorithms for agricultural, urban, and forested landscapes
3. Determine the differences in phosphorus storm dynamics for agricultural, urban, and forested landscapes

17. Methods, procedures, and facilities

Phosphorus is relatively expensive to measure, and requires time-intensive laboratory techniques that involve dangerous materials. However, phosphorus concentrations are often correlated to total suspended sediment (TSS) concentrations (Schuett report). While simple correlations between TSS and TP have been done before with at times limited success, we propose to use a rich dataset of UV-Vis absorbance spectra combined with nephelometric turbidity data to develop multivariate models that directly predicts TP and SRP.

Spectrophotometric sensors that measure light absorbance in the UV-Vis spectrum have a demonstrated ability to make continuous measurements of DOC, NO_3, and TSS concentrations in several types of surface waters (Fichot and Benner, 2011; Langergraber et al., 2003; Rieger et al., 2006; Sakamoto et al., 2009), and show promise for other parameters such as TP (Etheridge et al., 2014). Commercially available and field-rugged UV-Vis absorbance spectrophotometers create the possibility for researchers and managers to make rapid *in-situ* measurements of several key parameters at once. Development of *in-situ* optical sensor technology could allow for TP and SRP to be continuously measured on short timescales that capture rapid changes in hydrologic and biogeochemical processes critical to inform nonpoint source pollution control and TMDL management goals.

The Northeast Water Resources Network (NEWRnet) was formed by researchers in Delaware, Rhode Island, and Vermont to create a one-of-a-kind regional network of cutting edge high frequency *in-situ* water quality sensors. There is ongoing monitoring occurring at four sites in Vermont, targeting watersheds of various land uses. S::can spectrolyser™ spectrophotometers are currently installed at these four sites, and two of these sites are currently monitored for phosphorus concentrations. Precise and rapid UV-Vis absorbance measurements are collected from 220 nm to 750 nm in 2.5 nm increments. Optical path lengths were either 5 mm or 15 mm, depending on the typical turbidity at each site. To prevent biofouling, silicone wipers have been installed to automatically clean measurement windows before each measurement. In addition, the windows are cleaned by a technician at least every two weeks using DI water or pure ethanol. Sites are also equipped with YSI EXO-2 multi-parameter water quality sondes. These sondes collect nephelometric turbidity data, along with several other key water quality parameters such as pH, temperature, dissolved oxygen, conductivity, and fluorescent dissolved organic matter.

Generating algorithms to predict nutrient concentrations from UV-Vis absorbance spectra presents a challenge, due to the high dimensionality of the independent variables (absorbance spectra) compared to the single response variable (nutrient concentration). A statistical technique known as partial least squares regression (PLSR) has proven to be extremely useful in harnessing the information of a rich collection of independent variables to predict a desired dependent quantity. It is a technique that condenses independent variables into orthogonal, uncorrelated principal components, and then combines them in a multivariate model to predict the parameter of interest. PLSR was developed for a similar application (Wegelin, 2000), and was used by Etheridge et al. (2014) for a brackish marsh with encouraging results. Figure 1 shows preliminary results of our UV-Vis spectrophotometer measurements run through a PLSR algorithm to predict TP and SRP in the Missisquoi River watershed. This time series provides an unprecedented view of phosphorus dynamics on short timescales.

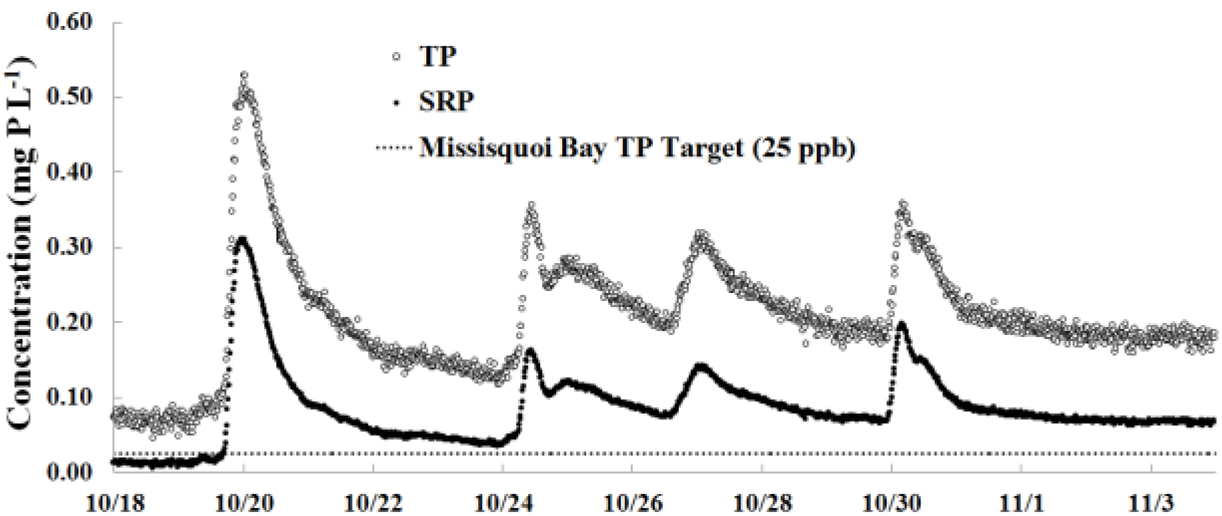


Figure 1. Preliminary data for TP and SRP show promising results. This plot shows TP and SRP concentrations predicted using UV-Vis absorbance spectra for Hungerford Brook (agricultural watershed) at 15-minute measurement intervals during multiple fall storms. This calibration performs reasonably well compared to SRP lab measurements ($R^2 = 0.61$, $p < 0.0001$), and is promising for TP ($R^2 = 0.35$, $p < 0.0001$). We are confident that performance can be improved by incorporating a greater number of laboratory measurements and *in-situ* nephelometric data into the multivariate model. The plot also shows that phosphorus concentrations in Hungerford Brook are well above targets for Missisquoi Bay, the receiving waterbody.

To leverage the recent advancements in this technology and to better understand how individual tributaries contribute to phosphorus loading, sensor performance must be improved by developing calibration algorithms to accurately determine phosphorus concentrations in a variety of land uses. We plan used existing infrastructure that targets primarily agricultural, urban, and forested streams individually. We utilized infrastructure installed by the NEWRnet project at Hungerford Brook (agricultural), Potash Brook (urban), and Wade Brook (forested) in addition to the main stem of the Missisquoi River (Figure 2). Three of these four sites are within the Missisquoi River watershed, which contributes a disproportionately high amount of phosphorus into Lake Champlain each year. UV-Vis absorbance spectra and nephelometric measurements are underway at 15-minute intervals at all of these sites. Any models predicting phosphorus concentrations developed as a result of this effort can be retroactively applied to measurements collected since spring of 2014, and applied to all future measurements.

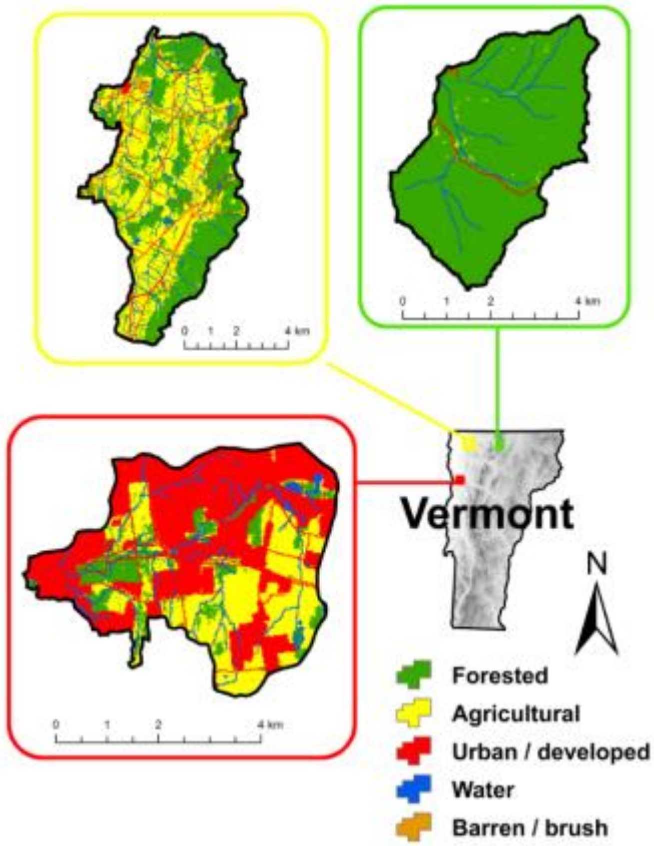


Figure 2. The outlets of these three watersheds are monitored as part of the NEWRnet consortium. Land use in these watersheds are primarily one of three main land uses of the region, including agricultural (Hungerford Brook), urban (Potash Brook), and forested (Wade Brook). Monitoring and grab samples will also take place on the main stem of the Missisquoi River. Developing methods to accurately measure TP and SRP *in-situ* at high frequencies at each site will offer unparalleled insights into phosphorus dynamics in the Lake Champlain watershed.

Grab samples were acquired to develop algorithms that relate sensor measurements with TP and SRP concentrations. Samples were collected at each site at least every two weeks, and by automated sampling during storm events. SRP was evaluated by molybdenum colorimetry with ascorbic acid modification (1995), and TP was evaluated using the EPA standard method 365.1 (1993b). Samples were evaluated for TSS using the EPA standard method 160.2 (1993a), where a well-mixed sample is filtered through a standard GF/F glass fiber filter, and the residue retained on the filter is dried to constant weight at 103 - 105 ºC. Samples were collected across a wide range of TP, SRP, and TSS values, so that robust calibrations could be developed.

18. Findings

Summary of Collected Data

During the 2016 field season, 132 samples were collected and analyzed for TP, TDP, and SRP along with concurrent *in-situ* UV-Vis spectrophotometer measurements. These samples were combined with other samples collected in previous years at the same locations, and summarized with descriptive statistics in Tables 1-3. Each analyte was significantly different among the agricultural, urban, and forested sites by the Kruskal-Wallis test ($p < 0.0001$ for all).

Table 1. Descriptive statistics for TP analyses at the three sites. All concentrations are in mg L^{-1}.

	Agricultural	Urban	Forested	Mixed
Count	36	27	43	15
Minimum	0.013	0.0065	0.00071	0.011
Maximum	0.92	0.090	0.021	0.032
Median	0.079	0.021	0.0038	0.020
Mean	0.13	0.025	0.0049	0.021
Variance	0.032	0.00035	0.000013	0.000056

Table 2. Descriptive statistics for TDP analyses at the three sites. All concentrations are mg L^{-1}.

	Agricultural	Urban	Forested	Mixed
Count	77	80	90	15
Minimum	0.0084	0.0035	0.0018	0.0066
Maximum	1.41	0.26	0.032	0.025
Median	0.063	0.032	0.0078	0.011
Mean	0.13	0.065	0.01069	0.012

	Agricultural	Urban	Forested	Mixed
Variance	0.042	0.0054	0.000057	0.000019

Table 3. Descriptive statistics for SRP analyses at the three sites. All concentrations are mg L^{-1}.

	Agricultural	Urban	Forested	Mixed
Count	77	105	90	15
Minimum	0.0030	0.00034	0.00060	0.0016
Maximum	1.24	0.23	0.023	0.016
Median	0.046	0.017	0.0043	0.0049
Mean	0.11	0.037	0.0068	0.0057
Variance	0.035	0.0026	0.000030	0.000015

Total Phosphorus Prediction
Using the PLSR calibration technique for TP using all available laboratory and uncompensated UV-Vis spectra at every site yielded a significant correlation ($p < 0.0001$) with an $R^2 = 0.42$, and standard error of 0.096 mg L^{-1} (Figure 3; n = 92).

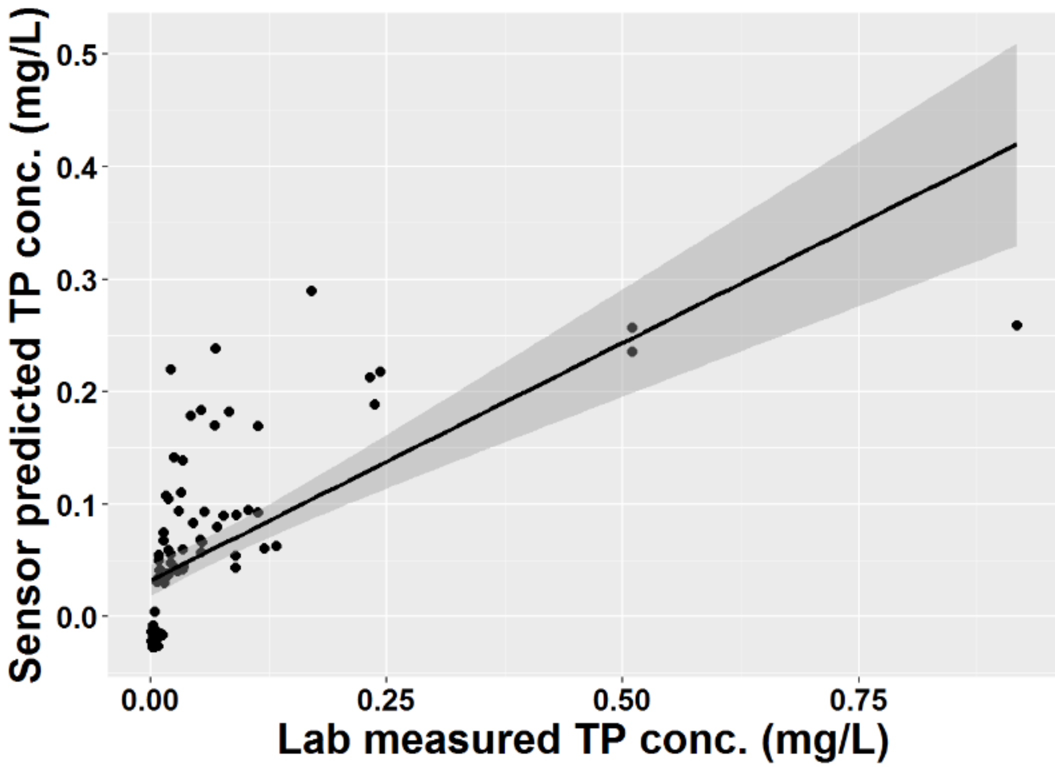
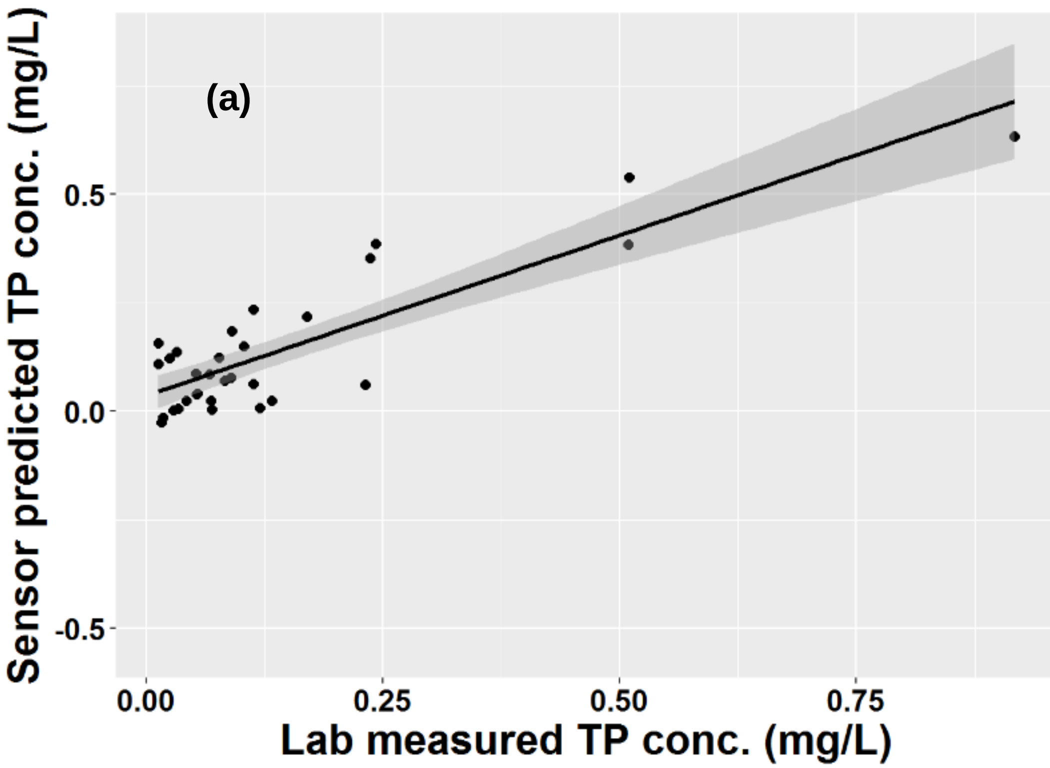
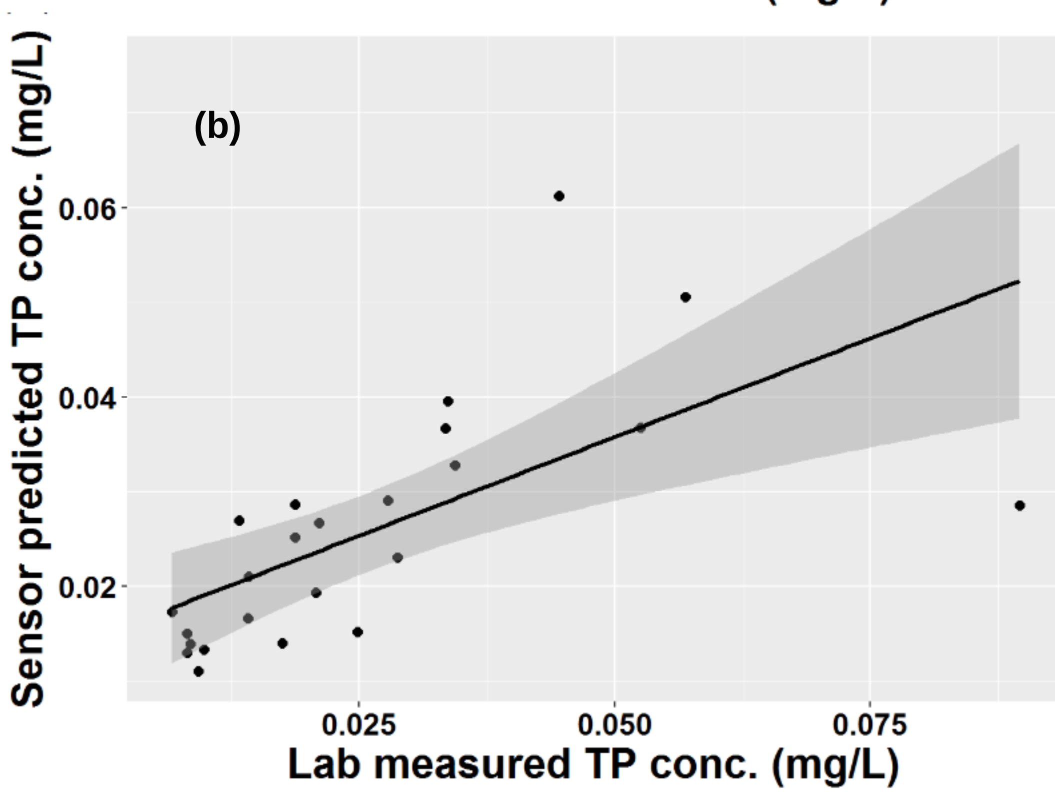


Figure 3. Sensor predicted TP concentrations vs. lab measured TP concentrations when all data are combined and uncompensated spectra are used. The shaded region represents a 90% confidence interval.

When TP calibrations were made with site-specific spectral data, predictions were improved at the agricultural and forested sites, but not for the urban site (Figure 4; Table 5). We had insufficient data to produce site-specific calibrations on the Missisqoui main stem.


(a)
Sensor predicted TP conc. (mg/L)
0.5
0.0
-0.5
0.00
0.25
0.50
0.75
Lab measured TP conc. (mg/L)


(b)
Sensor predicted TP conc. (mg/L)
0.06
0.04
0.02
0.025
0.050
0.075
Lab measured TP conc. (mg/L)

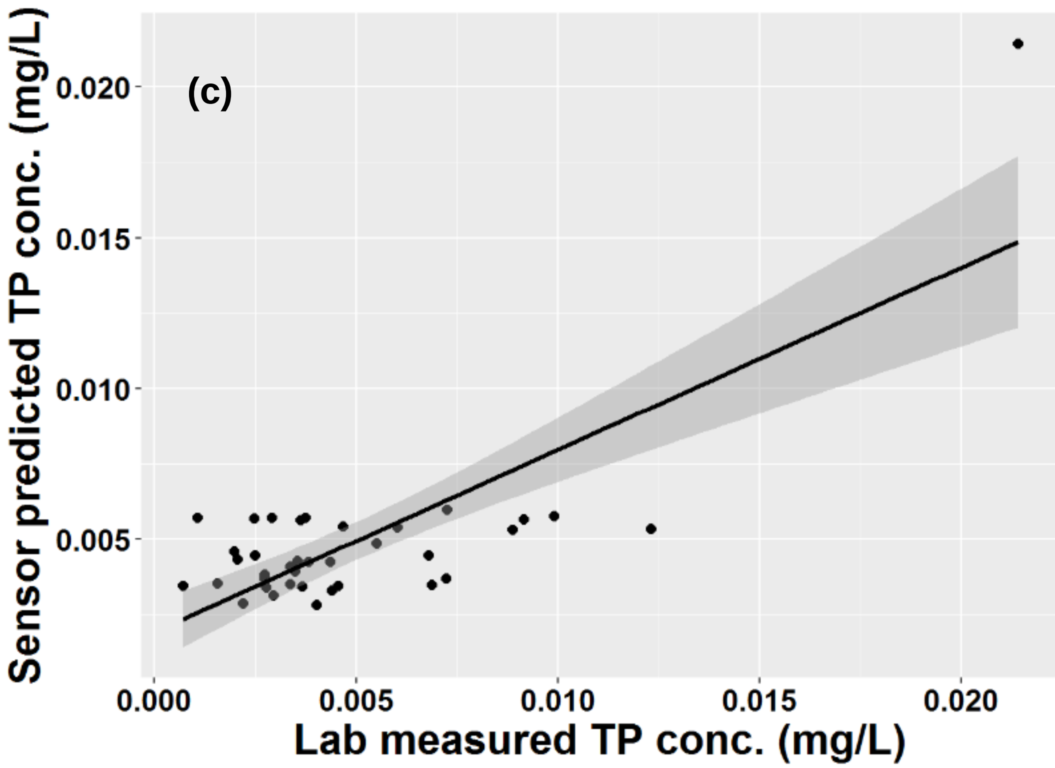


Figure 4. Sensor predicted TP concentrations vs. lab measured TP concentrations at the (a) agricultural, (b) urban, and (c) forested sites using turbidity compensated spectra. The shaded region represents a 90% confidence interval.

Table 5. Summary of calibration performance for TP when data are separated by site. Calibrations were made with three principal components and all relationships were highly significant ($p < 0.001$).

	R^2	Standard Error ($mg\ L^{-1}$)	Count
Agricultural (uncompensated)	0.69	0.106	31
Agricultural (compensated)	0.73	0.098	31
Urban (uncompensated)	0.39	0.015	24
Urban (compensated)	0.39	0.015	24

Forested (uncompensated)	0.58	0.0025	37
Forested (compensated)	0.59	0.0024	37

When TP calibrations were made with site-specific spectral data and nephelometric turbidity, discharge, and dissolved oxygen measurements were included in the PLSR independent variable matrix, little effect was made on the calibrations, and regression statistics were nearly identical to those without these additional measurements included.

Total Dissolved Phosphorus Prediction

Using the PLSR calibration technique for TDP using all available laboratory and uncompensated UV-Vis spectra at every site yielded a significant correlation ($p < 0.0001$) with an $R^2 = 0.50$, and standard error of 0.098 mg L^{-1} (Figure 5; n = 223).

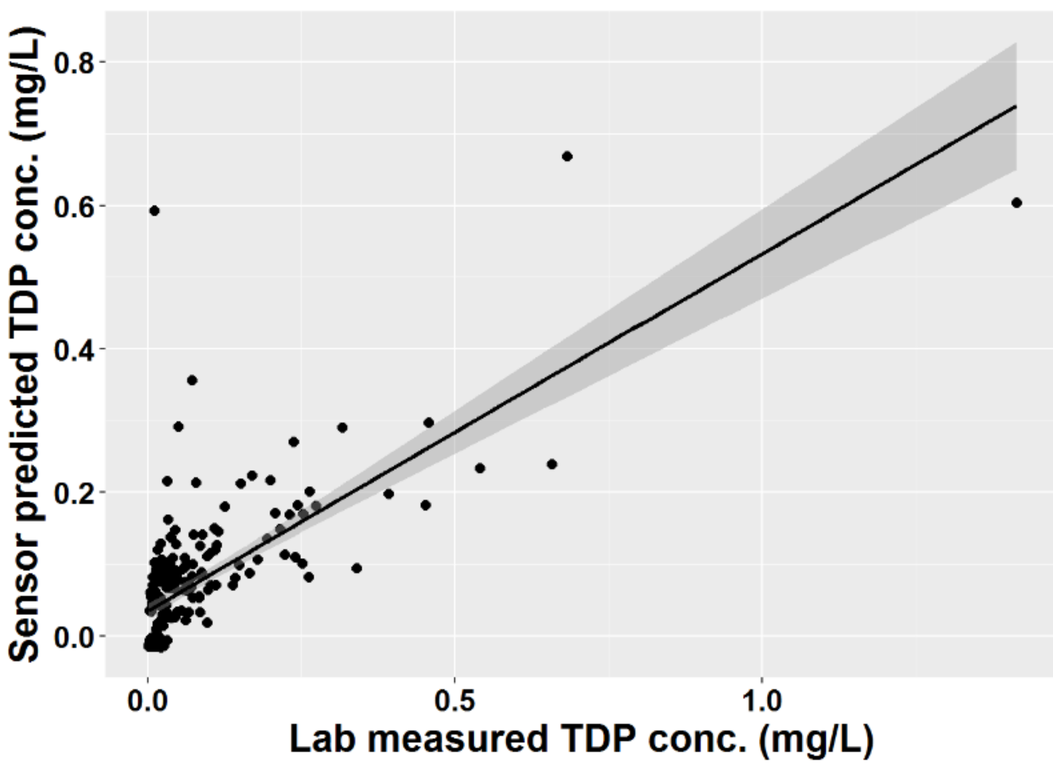
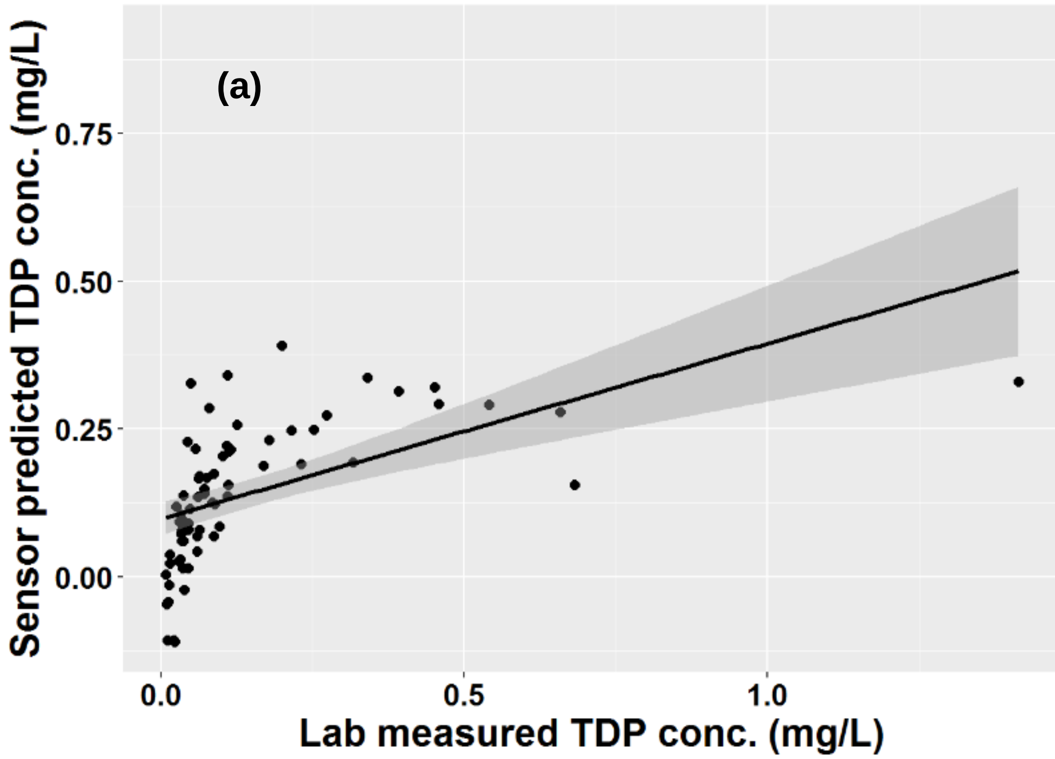
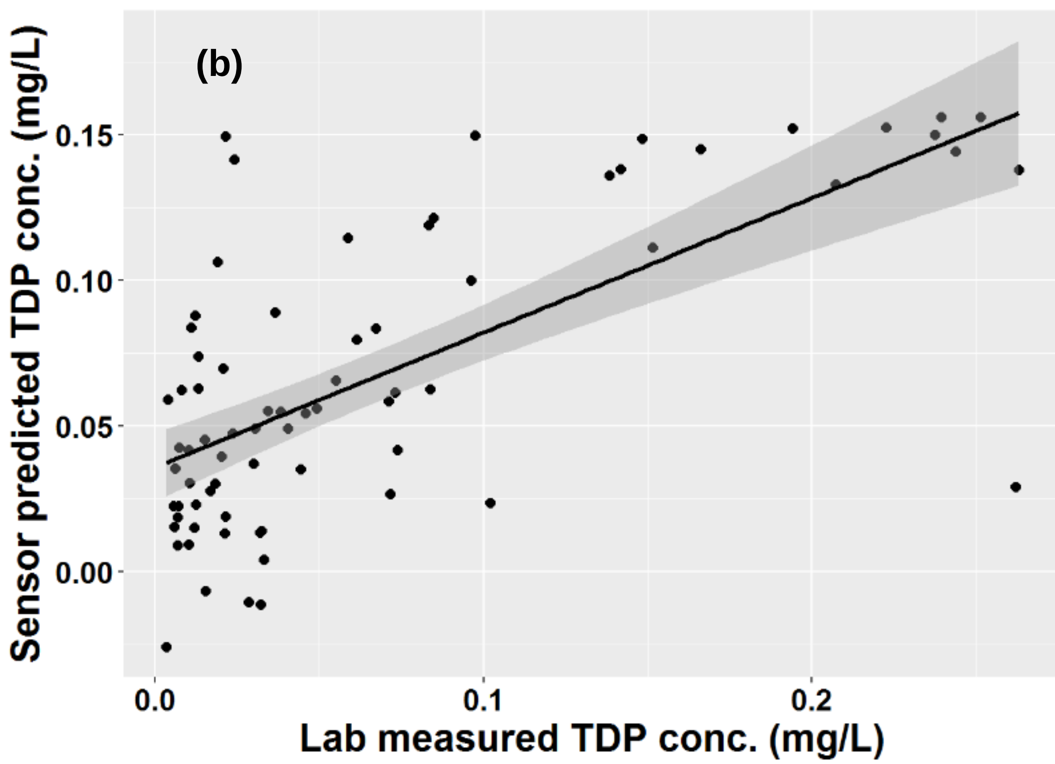


Figure 5. Sensor predicted TDP concentrations vs. lab measured TDP concentrations when uncompensated spectra are used. The shaded region represents a 90% confidence interval.

When TDP calibrations were made with site-specific spectral data, predictions were improved at all sites (Figure 6; Table 6).


(a)
Sensor predicted TDP conc. (mg/L)
0.75
0.50
0.25
0.00
0.0
0.5
1.0
Lab measured TDP conc. (mg/L)


(b)
Sensor predicted TDP conc. (mg/L)
0.15
0.10
0.05
0.00
0.0
0.1
0.2
Lab measured TDP conc. (mg/L)

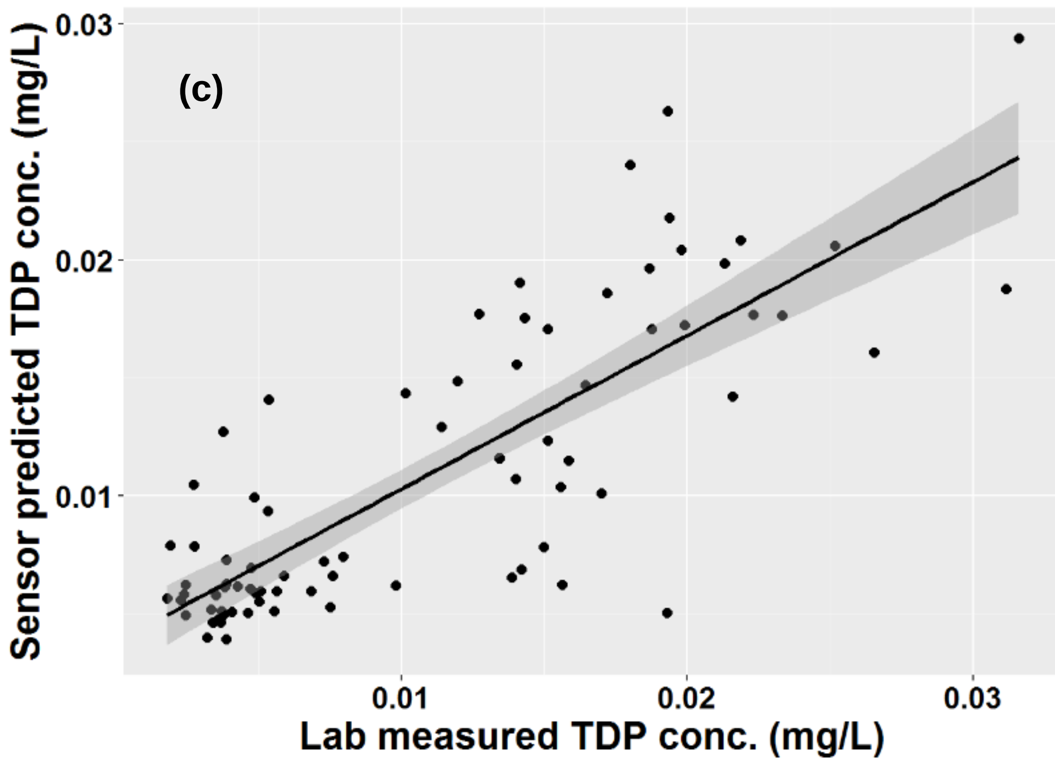


Figure 6. Sensor predicted TDP concentrations vs. lab measured TP concentrations at the (a) agricultural, (b) urban, and (c) forested sites. The shaded regions represent a 90% confidence interval.

Table 6. Summary of calibration performance for TDP when data are separated by site. Calibrations were made with four principal components and all relationships were highly significant ($p < 0.0001$).

	R^2	Standard Error ($mg\ L^{-1}$)	Count
Agricultural (uncompensated)	0.62	0.132	70
Agricultural (compensated)	0.7	0.117	70
Urban (uncompensated)	0.62	0.046	73
Urban (compensated)	0.69	0.042	73
Forested (uncompensated)	0.66	0.0045	80
Forested (compensated)	0.67	0.0043	80

When TDP calibrations were made with site-specific spectral data and nephelometric turbidity, discharge, and dissolved oxygen measurements were included in the PLSR independent variable matrix, little effect was made on the calibrations, and regression statistics were nearly identical to those without these additional measurements included.

Soluble Reactive Phosphorus Prediction

Using the PLSR calibration technique for SRP using all available laboratory and uncompensated UV-Vis spectra at every site yielded a significant correlation ($p < 0.0001$) with an $R^2 = 0.49$, and standard error of 0.084 mg L^{-1} (Figure 7; n = 248).

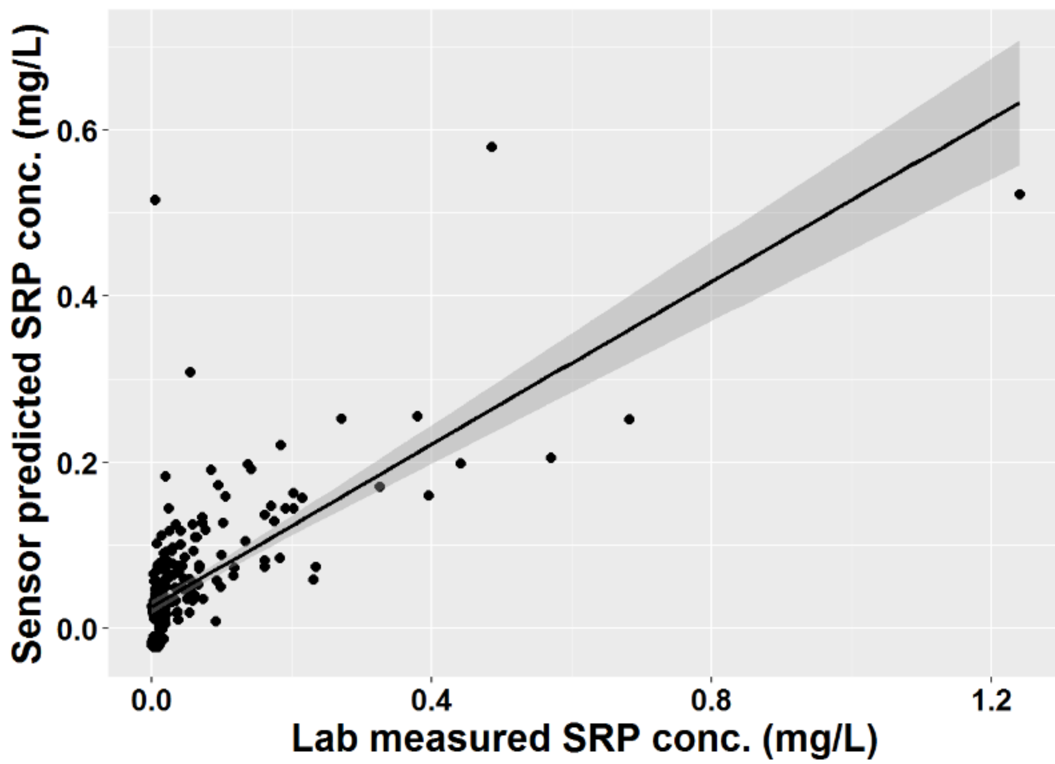
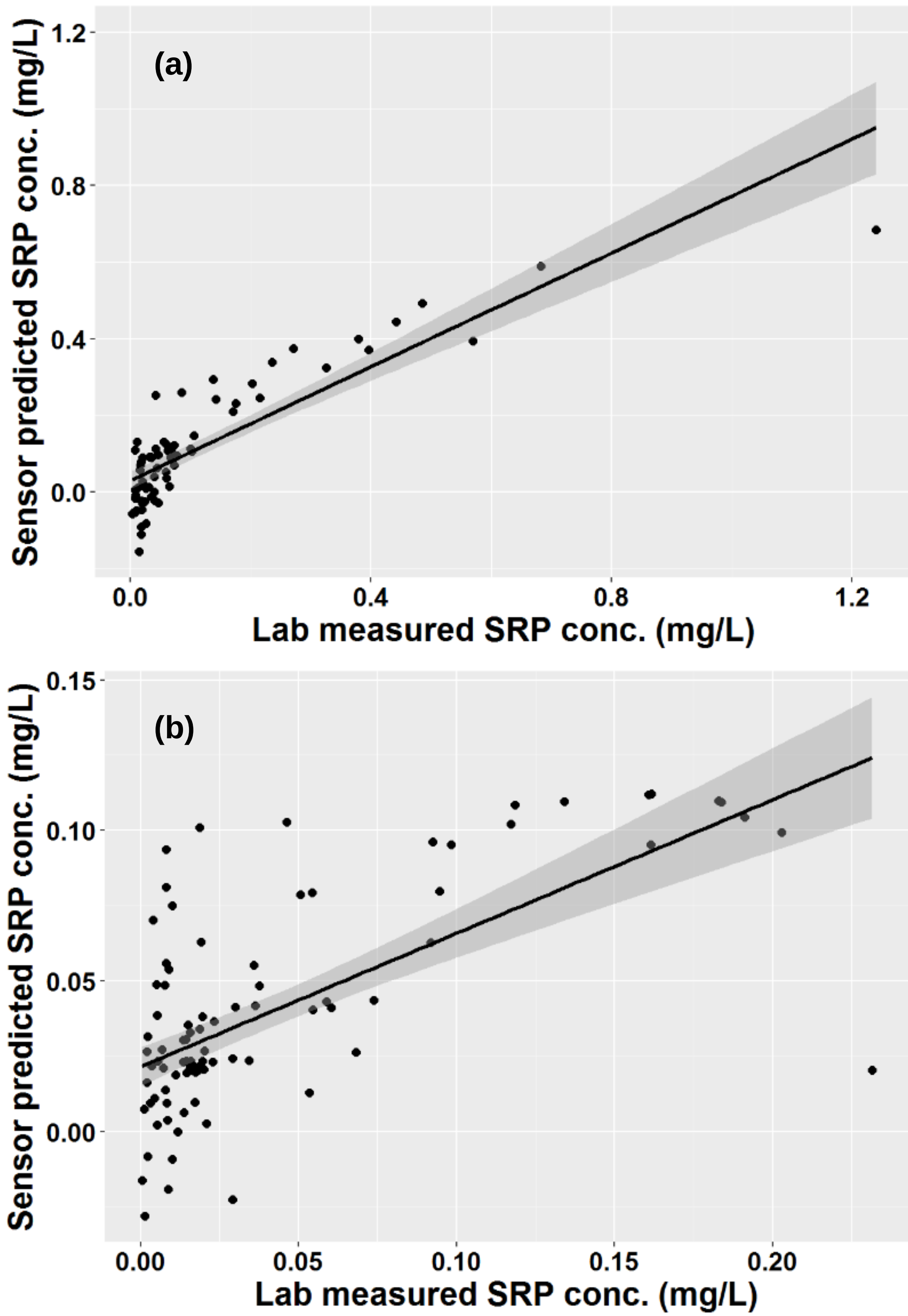


Figure 7. Sensor predicted SRP concentrations vs. lab measured TDP concentrations when uncompensated spectra are used. The shaded region represents a 90% confidence interval.

When SRP calibrations were made with site-specific spectral data, predictions were improved at all sites, besides the urban site when spectra turbidity compensated (Figure 8; Table 7).


(a)
Sensor predicted SRP conc. (mg/L)
Lab measured SRP conc. (mg/L)
0.0
0.4
0.8
1.2
(b)
Sensor predicted SRP conc. (mg/L)
Lab measured SRP conc. (mg/L)
0.00
0.05
0.10
0.15
0.20

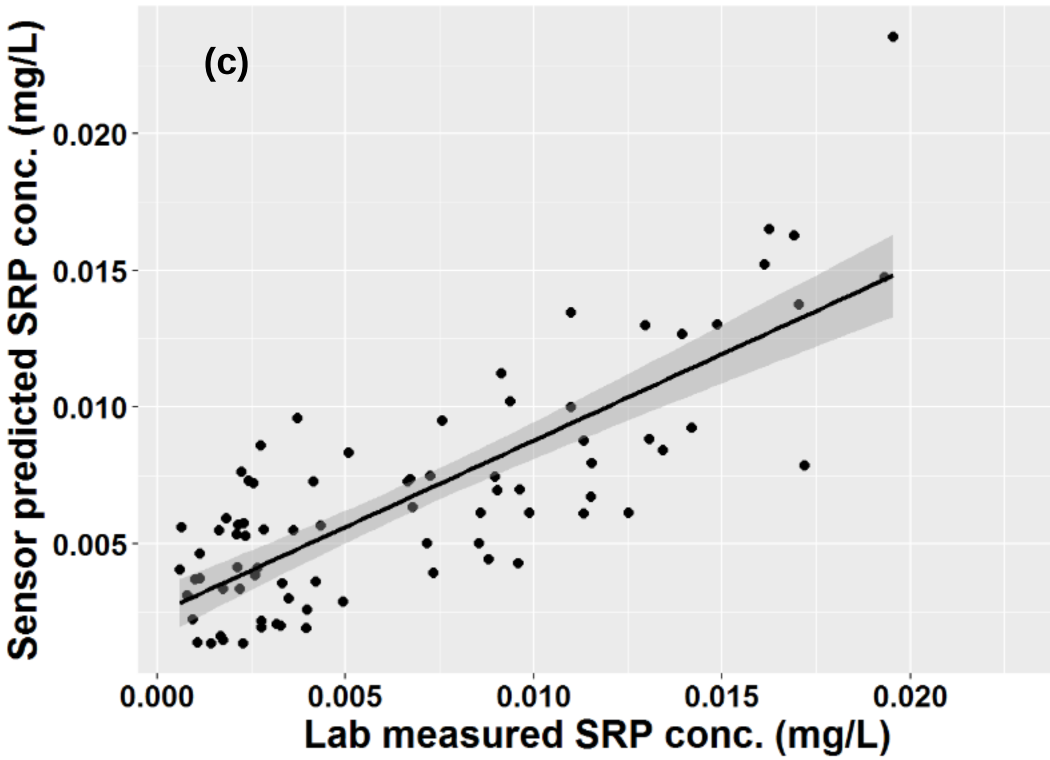


Figure 8. Sensor predicted SRP concentrations vs. lab measured TP concentrations at the (a) agricultural, (b) urban, and (c) forested sites. The shaded regions represent a 90% confidence interval.

Table 7. Summary of calibration performance for SRP when data are separated by site. Calibrations were made with four principal components and all relationships were highly significant ($p < 0.0001$).

	R2	Standard Error ($mg\ L^{-1}$)	Count
Agricultural (uncompensated)	0.66	0.11	70
Agricultural (compensated)	0.74	0.10	70
Urban (uncompensated)	0.56	0.035	98
Urban (compensated)	0.44	0.039	98

Forested (uncompensated)	0.62	0.0032	80
Forested (compensated)	0.63	0.0032	80

When SRP calibrations were made with site-specific spectral data and nephelometric turbidity, discharge, and dissolved oxygen measurements were included in the PLSR independent variable matrix, little effect was made on the calibrations, and regression statistics were nearly identical to those without these additional measurements included.

19. Discussion

To the authors' knowledge, this study represents the first attempt at using *in-situ* UV-Vis spectrophotometers to predict phosphorus species in streams draining agricultural, urban, and forested dominated streams. The fact that the concentrations for each analyte were significantly different indicates that our sites were an adequate testbed to compare the effects of each land use / land cover on sensor performance.

It is clear from our results that differences among the water chemistry matrices in each stream necessitated site-specific calibrations for each analyte. For some site and analyte combinations, predictions seemed to work best at relatively higher concentrations (e.g., SRP at the agricultural site; Figure 7a). For others, uncertainties were relatively constant across the full range of measured concentrations (e.g., TDP at the forested site; Figure 6c). Predictions of TDP and SRP generally explained roughly two-thirds of the variance in lab measured values, which is a promising result and should support the need for future investigation. The prediction of TP was less accurate than expected, since TP is known to correlate with turbidity, which acts as a proxy for TSS. Our best performing predictions were as accurate as those in Etheridge et al. (2014), which used similar equipment and methods in a brackish marsh ($R^2 = 0.73$ in that study, $R^2 = 0.39 – 0.73$ in this study). Results for TP from Schuett and Bowden (2014), which used acoustic Doppler current profiler backscatter to estimate TP, also fell into the range of variability for our results ($R^2 = 0.67$ in that study). Etheridge et al. (2014) also predicted SRP in a brackish marsh using similar equipment and methods and obtained results within the range of variability that we observed ($R^2 = 0.66$ in that study, $R^2 = 0.44 – 0.74$ in this study).

It was surprising to us that the inclusion of nephelometric turbidity, dissolved oxygen, and discharge measurements in PLSR models did not substantially improve the strength of phosphorus species predictions. We were hopeful that one or more of these variables would co-vary with phosphorus species of interest. It is possible that other measureable variables we did not monitor could provide further explanatory power in combination with UV-Vis spectra.

Our results indicate that *in-situ* UV-Vis spectrophometers can provide adequate estimated predictions of phosphorus species, though not without notable uncertainty. While site-specific calibrations improved predictions in all cases, UV-Vis spectrophotometers offer variable results depending on the conditions of each site. The predictions for TP were less accurate than expected, though did explain up to three-quarters of the variance at the agricultural site. This technique shows promise for dissolved species (TDP and SRP), and further work to measure other concurrent variables that may improve calibrations is warranted.

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Stumpf, R. P., Wynne, T. T., Baker, D. B., and Fahnenstiel, G. L., 2012, Interannual Variability of Cyanobacterial Blooms in Lake Erie: PLoS ONE, v. 7, no. 8, p. e42444.

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20. Investigator's qualifications

Matthew C. Vaughan

Education & Relevant Experiences

PhD – Natural Resources, University of Vermont (In Progress)
Study emphasis: *In-situ* optical water quality sensors, aqueous biogeochemistry

MS – Hydrologic Sciences, University of California, Davis (2013)
Study emphasis: Watershed hydrology, water quality, geomorphology

BA – Physics, Middlebury College (2009)
Study emphasis: Renewable energy, electromagnetism, astrophysics

University of Vermont, Rubenstein Ecosystem Sciences Laboratory — Burlington, VT
Graduate Research Assistant (March 2014 – present)

- Manage a four-person field survey campaigns throughout northern Vermont
- Install and maintain autonomous state of the art water quality monitoring equipment
- Develop programs to relate optical absorbance spectra to nutrient concentrations
-

University of California, Davis, Hydrologic Sciences Graduate Group — Davis, CA
Graduate Research Assistant (Fall 2012 – February 2014)

- Managed a three-person, four-month field survey campaign in the Sierra Nevada mountains
- Installed and maintained monitoring equipment in a remote location for flood research
- Analyzed field data and conducted an extensive literature review
- Synthesized findings to develop a new conceptual model for watershed-scale streamwood storage

Junior Specialist (Summer 2012)

- Digitized elements of aerial imagery in ArcGIS
- Coupled results of GIS analysis with a high-resolution 2D hydraulic river model
- Conducted statistical analysis of remotely sensed data
- Reported findings to the US Army Corps of Engineers and other stakeholders

Publications & Presentations

<u>Conference Presentations</u>

Vaughan, M.C., Schroth A.W., Bowden, W.B., Jerram, A., Shanley, J.B., Vermilyea, A., Observing Nutrient Dynamics in Streams Draining Varied Land Uses Using *In-Situ* Optical Sensors, Abstract H11B-0867 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15-19 Dec.

Gold, A., Schroth, A.W., Inamdar, S.P., Addy, K., Bowden, W.B., Andres, S., Levia, D.F., Vermilyea, A., Leathers, D.J., Garfield, M., Chace, J., Jerram, A., **Vaughan, M.C.**, Shanley, J.B. (2014), North East Water Resources Network (NEWRnet): A real-time water quality sensor network to study impacts of climate variability for Delaware, Rhode Island, and Vermont, Abstract H11B-0865 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15-19 Dec.

Vaughan, M.C., Pasternack, G.B., Senter, A.E., Dahlke, H.E. (2013), Large Wood Storage Does Not Decrease Downstream Through a Watershed, Abstract EP43A-0824 presented at 2013 Fall Meeting, AGU, San Francisco, Calif., 9-13 Dec.

Technical Reports

Vaughan, M.C., Pasternack, G. B., Senter, A. E., Dahlke, H. E. 2014. Local and watershed controls on large wood storage in a mountainous stream network. Prepared for the U.S. Army Corps of Engineers, Sacramento District. University of California at Davis, Davis, CA., 54pp.

Vaughan, M. C. and Pasternack, G. B. 2014. Aerial mapping of streamwood and human-built detritus available as cover in the lower Yuba River in autumn 2008. Prepared for the Yuba Accord River Management Team. University of California, Davis, CA., 22pp.

Martindill, J., **Vaughan, M. C.**, Pasternack, G. B. 2014. November-December 2012 stream video monitoring report for camera below Englebright Dam. Prepared for the U.S. Army Corps of Engineers, Sacramento District. University of California at Davis, Davis, CA., 9pp.

Vaughan, M. C., Senter, A. E., Pasternack, G. B. 2014. Streamwood storage in the reservoirs of the Upper Yuba River watershed, Fall 2013. Prepared for the U.S. Army Corps of Engineers, Sacramento District. University of California at Davis, Davis, CA., 3pp.

Vaughan, M. C., Pasternack, G. B., Senter, A. E., Dahlke, H. E. 2013. Large streamwood storage does not decrease downstream through a watershed. Prepared for the U.S. Army Corps of Engineers, Sacramento District. University of California at Davis, Davis, CA., 64pp.

Senter, A. E., **Vaughan, M. C.**, Pasternack, G. B. 2013. Streamwood surveys in New Bullard's Bar Reservoir – 2013. Prepared for the U.S. Army Corps of Engineers, Sacremento District. University of California at Davis, Davis, CA., 2pp.

Senter, A. E., **Vaughan, M. C.**, Pasternack, G. B. 2012. Streamwood surveys in New Bullard's Bar Reservoir – 2010 and 2012. Prepared for the U.S. Army Corps of Engineers, Sacremento District. University of California at Davis, Davis, CA., 2pp.

Manuscripts in preparation

Vaughan, M.C., Pasternack, G.B., Senter, A.E., Dahlke, H.E. Local and watershed controls on large wood storage in a mountainous stream network.

Vaughan, M.C., Pasternack, G.B., Senter, A.E. Discharge threshold causes hydraulic sorting of large wood in a mountain watershed.

BEVERLEY C. WEMPLE

Education

Institution	Location	Major/Minor	Degree & Year
Oregon State Univ	Corvallis,OR	Forest Science/Bioresource Engineering	Ph.D., 1998
Oregon State Univ	Corvallis, OR	Physical Geography/Geog Techniques	M.S., 1994
Univ of Richmond	Richmond, VA	Economics and German	B.A., 1986

Academic Appointments

Associate Professor, Department of Geography. Secondary faculty appointment in Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT. 2005-present.

Assistant Professor, Department of Geography, University of Vermont, Burlington, VT. 1999-2005.

Postdoctoral Fellow, USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR. 1998-1999.

Graduate Research Assistant**,** Department of Forest Science, Oregon State University, Corvallis, OR. 1993-1998. Department of Geosciences, Oregon State University, Corvallis, OR. 1991-1993

Selected Publications

Mohammed, I. N., A. Bomblies, and B. C. Wemple. 2015. The use of CMIP5 data to simulate climate change impacts on flow regime within the Lake Champlain Basin, J. Hydrol. Reg. St., 3, 160-186, doi:10.1016/j.ejrh.2015.01.002.

Pechenick, A., D. M. Rizzo, L. A. Morrissey, K. Garvey, K. Underwood and B. C. Wemple. 2014. A multi-scale statistical approach to assess the effects of hydrological connectivity of road and stream networks on geomorphic channel condition. Earth Surface Processes and Landforms, DOI 10.1002/esp3611.

Penn, C. A., B. C. Wemple, and J. L. Campbell, 2012. Forest influences on snow accumulation and snowmelt at the Hubbard Brook Experimental Forest, New Hampshire, USA. Hydrologic Processes, 26, 2524–2534, DOI: 10.1002/hyp.9450.

Jones, J.A., G.L. Achterman, L.A. Augustine, I.F. Creed, P.F. Ffolliott, L. MacDonald, B.C. Wemple, 2009. Hydrologic effects of a changing forested landscape – challenges for the hydrological sciences. Hydrological Processes, 23: 2699-2704. DOI: 10.1002/hyp.7404.

Wemple, B. C., J. Shanley, J. Denner, D. Ross, and K. Mills. 2007. Hydrology and water quality in two mountain basins of the northeastern US: assessing baseline conditions and effects of development. Hydrological Processes, DOI: 10.1002/hyp.6700.

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Waichler, S. R., B. C. Wemple, and M. S. Wigmosta, 2005. Simulation of water balance and forest treatment effects at the H. J. Andrews Experimental Forest. Hydrological Processes. 10.1002/hyp.5841.

Dutton, A. L., K. Loague, and B.C. Wemple, 2005. Simulated effect of a forest road on near-surface hydrologic response and slope stability, Earth Surface Processes and Landforms, 30: 325-338. DOI: 10.1002/esp.1144.

Wemple, B. C. and J. A. Jones, 2003. Runoff production on forest roads in a steep, mountain catchment, Water Resources Research, 39(8), 1220, doi 10.1029/2002WR001744.

Wemple, B. C., F. J. Swanson, and J. A. Jones, 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon, Earth Surface Processes and Landforms, 26: 191-204.

Synergistic Activities

Outreach and consultation –Member of a National Research Council study committee assembled to assess the effects of forest management on the nation's water resources, 2006-2008. Provide outreach and consultation to soil scientists, hydrologists, technicians, and other professionals of the U.S. Forest Service, Bureau of Land Management, state (Vermont, Oregon, Washington) natural resource agencies, and non-governmental organizations (Nature Conservancy, Oregon Natural Resources Council, National Fish and Wildlife Foundation), 1999-present. Consultation with Fundación Cordillera Tropical (Cuenca, Ecaudor) on development of hydrologic monitoring program for northern tropical Andes, 2013-present.

Modeling applications to hydrological problems – collaborate with hydrologic modelers at Stanford University and Pacific Northwest National Lab to develop and test rainfall-runoff models to improve understanding of forest hydrologic processes and effects of forest management activities.

Innovations in teaching and training – Developed Geospatial Analysis and Hydrologic Modeling workshop for Chilean and Argentinian graduate students as part of NSF-funded SAVI grant to Dr. T. Harmon (UC Merced), delivered in Coyhaique, Chile April 2014. Developed five day *Hydrologic Modeling* workshop for graduate students with NSF Vermont-EPSCoR support, 2008. Developed NSF-supported interdisciplinary undergraduate *Watershed Field Science* (with Bierman, Druschel, Rizzo and Watzin), 2007-2009.

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ACADEMIA

-Assistant Professor of Chemistry at Castleton University, Castleton, VT
Aug. 2011 - present

-Post Doctoral Fellow at University of Alaska Southeast, Juneau, AK
Eran Hood (primary) and Durelle Scott (Virginia Tech)
Nov. 2009 - Aug. 2011

- Colorado School of Mines, Golden, CO
Ph.D. in Geochemistry   Graduation: August 2009
Advisor: Bettina M. Voelker

- Hamilton College, Clinton, NY
B.A. in Chemistry (Minor in Geology)   Graduation: May 2004
Advisor: Michael McCormick

AWARDED GRANTS

$38,856 – Aug 2013-16, NSF EPSCoR North East Water Resources Network Research Grant, Subaward

$34,528 – March 2013-14, Vermont Genetics Network, NIH
"Indirect photochemical decay of BPA in sunlit surface waters"

$8,325 – March 2013-14, Vermont Genetics Network, NIH
Student Summer Research Grant on behalf of Ashley Acuna

$2,424 - February 2013, Castleton Faculty-Student Research Grant
"Riparian Net Ecosystem Production in Varying Conditions"

$589 - October 2012, Castleton Faculty-Student Research Grant
"Evaluation of the potential for wind energy at Castleton"

$1,539 – May 2012, Castleton Faculty Advanced Study Grant
"Development of BPA Analysis"

$36,530 – March 2012-13, Vermont Genetics Network, NIH
"Indirect photochemical decay of BPA in sunlit surface waters"

$10,000 – February 2012, Pittcon National College Grant
"PicoSpin NMR for Organic and Analytical Chemistry Labs"

$79,500 - December 2011, NSF Earth Sciences: Instrumentation and Facilities"Acquisition of instrumentation to support research and undergraduate training in hydrology and biogeochemistry at the UAS"

$2,500 – October 2011, Castleton Faculty-Student Research Grant
"Installation of a stream gauge"

SYNERGISTIC ACTIVITIES

-Environmental Science Program Coordinator (2012-present)
-Development of B.S. in Chemistry major at Castleton (started Fall 2014)
-Instructor in Castleton's First Year Seminar Program (FYS) (Fall 2013-present)
-Organizer/Founder of NAS Department Research Fair and Year End Award Ceremony (2012-present)

-Journal reviewer for: *Environmental Science & Technology, Marine and Freshwater Chemistry,*and *Biogeochemistry* (2009-present)
-Research advisor for 16 undergraduate students (2012-present)
-President's Sustainability Action Committee, Co-Chair (2012-present)

PUBLICATIONS

Spencer, R. G. M.; **Vermilyea, A.W.**; Fellman, J.; Raymond, P.; Stubbins, A.; Scott, D.; Hood, E. **2014** Seasonal variability of organic matter composition in an Alaskan glacier outflow: Insights into glacier carbon sources. *Environmental Research Letters.* 9(5):055005.

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Quantifying the consequences of water quality changes and habitat fragmentation on the genetic structure of aquatic organisms in the Lake Champlain basin

Basic Information

Title:	Quantifying the consequences of water quality changes and habitat fragmentation on the genetic structure of aquatic organisms in the Lake Champlain basin
Project Number:	2016VT81B
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End Date:	7/31/2017
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Congressional District:	Vermont-at-Large
Research Category:	Biological Sciences
Focus Category:	Ecology, Conservation, Recreation
Descriptors:	None
Principal Investigators:	J Ellen Marsden, Peter Euclide

Publications

There are no publications.

13. Title: Quantifying the consequences of water quality changes and habitat fragmentation on the genetic structure of aquatic organisms in the Lake Champlain basin

14. Statement of regional of state water problem:

How population diversity is distributed across landscapes has been a key question in ecology for more than a century, stimulating research to describe the effect of both natural and man-made barriers on population distributions and genetic structure (Forman 1995). Habitat fragmentation and degradation have increased as human populations continue to expand (With & Crist 1995; Ewers & Didham 2006). Fragmentation damages ecosystems by changing ecosystem services, promoting dispersal of exotic species, and damaging core habitat (Trombulak & Frissell 2000; Broadbent et al. 2008). Further, fragmentation is one of the root causes of increasing rates of species extinctions (Fahrig 1997; Henle et al. 2004). Fragmented landscapes reduce gene flow and dispersal among sub-populations, weakening species' ability to adapt to changes in their environment (Elliot et al. 2014; Macarthur & Wilson 1967; Templeton et al. 1990).

In aquatic systems, there has been extensive research on riverine habitat fragmentation by dams and the impact of these dams on fish movement, habitat connectivity, and habitat loss due to changes in water quality, hydrology and sediment transport (Ligon et al. 1995; Bessert & Orti 2008; Wang et al. 2010). Understanding how dams impact fish movement and fragmentation has allowed for better conservation and management of many river species, such as instalation of fish passage systems, changes in dam outflow practices, and dam removals. Without a clear understanding of the fragmentation pressures present in rivers, these improved practices would have been difficult to develop and implement.

In contrast to rivers, lakes are generally not subject to fragmentation, making it difficult to predict how lake hydrology and lake species might react to fragmentation pressure. Causeways are the lentic equivalent of dams, and are often constructed without openings, limiting the movement of nutrients and organisms. Most causeways connect islands to the mainland across marine ecosystems (e.g., connecting Venice, Singapore, and Bahrain to the mainland), or are used to reclaim land or protect land from tidal flooding (e.g., the system of polder dykes and Zuiderzee works in the Netherlands). However, causeways, are uncommon in freshwater lakes. When present, causeways fragment lentic environments and may limit the movement of aquatic species, thereby limiting gene flow (Fechhelm 1999; Fechhelm et al. 1999), similar to roads, deforestation, or other terrestrial landscape-altering practices. Lacustrine causeways, such as the Southern Pacific Railway across Great Salt Lake, can also have significant effects on hydrology and chemistry, and therefore the water quality of lakes. Studying causeway fragmentation in freshwater lakes provides a novel opportunity to study the consequences of whole-lake fragmentation on the population structure of aquatic organisms. Elucidating how fragmentation pressures in lakes varies from rivers could lead to improved management practices in Lake Champlain akin to those that have been developed in rivers.

History of fragmentation in Lake Champlain:

Lake Champlain has a long history of fragmentation. Geologically, the Champlain Valley has experienced extensive change over the last 20,000 years. During this time, Vermont experienced glaciation, complete changes in lake outflow direction, large fluctuations in lake size, and even changes in salinity when, for a 1,500 to 2,000 year period, the region was connected to the Atlantic Ocean (Langdon et al. 2006). Following European colonization in the 1700s many dams and weirs were built in the Vermont tributaries of Lake Champlain, and causeways were being constructed in the lake by the mid-1800s. The causeways divide the lake into four distinct basins and may be partially responsible for large differences in productivity and water quality among basins (Myer and Gruendling 1979).

Fall line

The Lake Champlain drainage has a distinct fall line that runs north to south, parallel to the lake on the Vermont side. The fall line is approximately 46 m in elevation and has resulted in major waterfalls in tributary rivers. These falls have acted as a natural barrier to the movement of fish since the time of Lake Vermont, 12,500 years ago (Marsden & Langdon 2012).

Dams

During the 1800s, dams were built on most of the major tributaries to Lake Champlain, including the Great Chazy, Little Chazy, Salmon, Little Ausable, Ausable, Boquet, Winooski, Lamoille, and Missisquoi rivers and Otter Creek. Though many of the smaller weirs and mill dams were removed, there remain 463 dams in the Lake Champlain watershed. Additionally, dams built on the Lamoille and Winooski rivers were built below the natural fall line and cut off fish from quality spawning habitats (Marsden & Langdon 2012). These dams have impacted the populations of many fish including salmon, lake sturgeon, redhorses, suckers and lake whitefish.

Causeways

Since the mid-1800s, construction of nine major causeways has progressively divided Lake Champlain into relatively isolated regions (Northeast Arm, Malletts Bay, Cary Bay, The Gut, Missisquoi Bay, and the northern section of the northwest arm; Figure 1). The causeways range from 300 m to 5.25 km long; all have narrow openings (24 to 250 m) to allow passage of boat traffic (Marsden & Langdon 2012). The openings are generally shallow (2-4 m deep) and therefore may be inaccessible to cold-water fish species during lake stratification when surface waters are warm. Causeways on either side of Cary Bay and the Gut (which separate the North East Arm from the Main Lake) are relatively shallow and become stagnant and heavily vegetated in the summer because of the restricted flow. These seasonal changes may exacerbate the existing barrier to fish movement by lowering the habitat suitability for cold, clearwater fish.

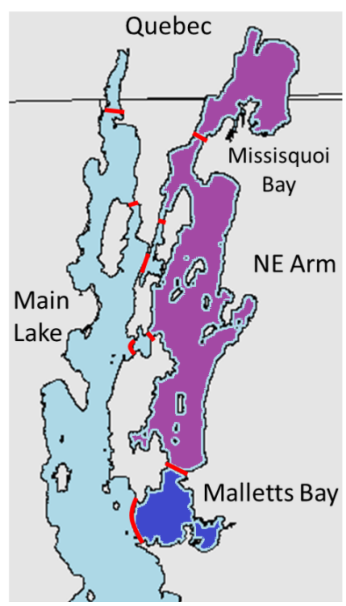

Figure 1: Main Lake (light blue), the North East Arm (purple) and Malletts Bay (dark blue) basins of Lake Champlain. All causeways are indicated as red lines on the map.

Causeways have been the point of much contention in Vermont; although they provide many services such as vehicle transit across the lake and nursery habitat for endangered turtles, causeways have also been found to be partially responsible for the high nutrient levels that cause algal blooms in Missisquoi Bay. This discovery led to the widening of the opening in the Missisquoi Bay causeway in 2004.

Evidence of fragmentation impact

Despite the long history of habitat fragmentation in the region, very little research has been conducted to assess its impact on local fauna and water quality. The response of local fauna can be an important indicator of larger system-wide issues exacerbated by fragmentation, such as reduction of water flow and consequent changes in water quality. For example, limited water flow into and out of Missisquoi Bay due to the causeway at the outlet to the bay contributed to nutrient and sediment concentration and accelerated eutrophication. Walleye (*Sander vitreus*) and lake whitefish (*Coregonus clupeaformis*) have declined in the bay over the last century, apparently in response to poor water quality and spawning habitat degradation (Marsden et al. 2010, Marsden and Langdon 2012). Lake trout (*Salvelinus namaycush*) were historically stocked into the Inland Sea but did not remain there. They are occasionally caught in the Inland Sea in winter, which indicates that they can pass through the causeways, so their absence in the Inland Sea may be related to poor water quality. In recent years, potential indications of lake and river fragmentation have been noted by state agencies and researchers. Three fish in particular have been suggested to be impacted by lake and/or river habitat fragmentation. missing caption below – and need to move this lower, after first mention in the text

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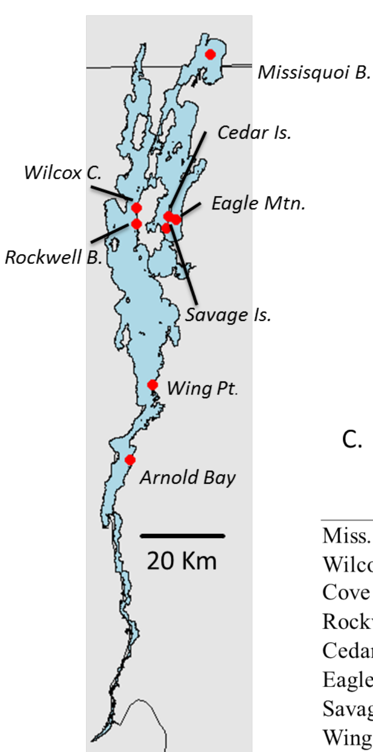

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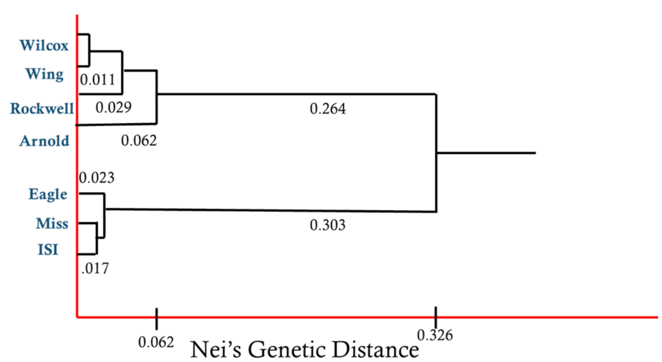

C.

	Miss. Bay	Wilcox Cove	Rockwell B.	Cedar Island	Eagle Mtn.	Savage Is.	Wing Point
Miss. Bay							
Wilcox Cove	0.187						
Rockwell B.	0.177	0.046					
Cedar Island	0.012	0.187	0.187				
Eagle Mtn.	0.017	0.198	0.193	0.014			
Savage Is.	0.102	0.262	0.254	0.106	0.121		
Wing Point	0.177	0.013	0.252	0.177	0.190	0.252	
Arnold Bay	0.111	0.051	0.188	0.115	0.125	0.188	0.051

Figure 2: Summary of whitefish genetic study. A) sampling locations of whitefish in Lake Champlain. B) Dendrogram showing the genetic distance, note differences between Main Lake and Northeast Arm. C) Table of pairwise Fst values, underlined values indicate comparisons between Main Lake and Northeast Arm. Parent, Marsden et al. *unpublished data*.

Whitefish
Lake whitefish were historically a commercially prized fish in Lake Champlain (Marsden and Langdon 2012). The fishery closed in 1912 and little research was conducted on the species until 2010 (Herbst et al. 2011). In 2013, larval lake whitefish were sampled at several sites in the Northeast Arm and Main Lake. Using microsatellite markers, whitefish populations were shown to cluster into two to three genetic groups separated by Grand Isle and the Island Line and Sandbar causeways (Figure 2). The presence of genetically different groups suggests that causeways could be impacting the movement whitefish enough to impair gene flow among regions of the lake. If whitefish are indeed experiencing population isolation due to causeways, it is likely other fish are as well.

Rainbow Smelt
Rainbow smelt (*Osmerus mordax*) are an important forage fish that provide a substantial food source for large game fish such as lake trout, Atlantic salmon, and walleye in Lake Champlain. Every year the Vermont Department of Fish and Wildlife conducts index sampling of forage fish populations in the lake. During this assessment, smelt abundance is measured using hydroacoustics and trawling at five sites throughout the lake, including in some isolated basins, (i.e., Malletts Bay and the Northeast Arm). The index sampling indicated that the population abundance of smelt in Malletts Bay, the Northeast Arm, and the Main Lake all varied independently in some years, suggesting that the populations are not readily intermixing. This lack of intermixing may be a consequence of habitat fragmentation. However, preliminary genetic results suggest that there is no quantifiable genetic structure in the Lake Champlain smelt population, which could mean that enough smelt are able to pass through the causeway openings to maintain a genetically mixed population.

Walleye
According to the Vermont Department of Fish and Wildlife, populations of walleye have been in a slow decline over the last few decades (Marsden et al. 2010). However, due to a lack of data, the causes of the decline are difficult to identify. Before the construction of lake causeways, walleye were reported to migrate along the eastern shore of Lake Champlain to spawn in the Lamoille and Missisquoi rivers, passing between Grand Isle and the mainland. In 1850, a causeway was built connecting mainland Vermont to Grand Isle with no opening to allow passage. Presumably this causeway either blocked fish passage to the rivers entirely or forced fish to migrate the much longer distance around Grand Isle to reach spawning habitat, potentially impacting spawning site arrival time or reproductive output. Though many factors likely contribute to this observed decline in walleye, understanding how causeways are affecting fish access to spawning habitat is an important step in identifying causes of the decline.

Eutrophication
Lake Champlain was historically an oligotrophic or mesotrophic lake before European settlement, but became increasingly eutrophic throughout the 1900s (Levine et al., 2012). As eutrophication of the Northeast Arm of the lake continues, new monitoring techniques have been implemented to identify the source of nutrients (Facey et al., 2012) and triggers of

harmful algal blooms (Fortin et al., 2015). However, very little research has been conducted on determining how large, basin-level differences in water quality and nutrients may be associated with the reduction in water flow caused by causeway barriers, and may impact higher trophic-level species such as fish. Understanding how fish move among basins, and how their movements are influenced by differences in water quality among basins, is an important step in understanding potential long-term impacts of changes in basin-specific productivity on fish populations.

15. Statement of results or benefits:

Our aim is to quantify the magnitude of habitat fragmentation impact caused by lake causeways. Causeways may be physical barriers to fish movement, or may alter water quality in isolated basins by reducing water flow between them. However, because very little is known about the barrier pressure of causeways, a first step is to evaluate how changes in genetic structure resulting from causeway fragmentation compare to genetic changes known to be caused by stream barriers. We will evaluate the relative impact of causeways on population genetic structure of a model species by comparing the genetic structure of populations of this species isolated in the lake by causeways (built since the 1850s) with populations isolated by well-established barriers in rivers, i.e., dams built since the early 1800s, and the natural fall line, which isolated populations 13,000 years ago. We hypothesize that our model fish species will be impacted differently by lake versus riverine habitat fragmentation. Because dams were constructed prior to causeways and are a complete barrier to fish movement (at least in one direction), while causeways are semi-permeable and likely form a resistance barrier of depth, temperature, water chemistry and water quality rather than a complete physical barrier (McRae 2006), we predict that genetic differences between populations fragmented by dams will be greater than populations fragmented by causeways. Further, we predict that there will be a larger signature of isolation between populations separated by the fall line than those separated by dams or causeways. Specifically, we expect higher Fst and more private alleles in populations that have been separated over several thousand years by the fall line, compared with populations more recently separated by dams in the same river systems. If populations separated by causeways in Lake Champlain show similar or larger differences than populations separated by dams, then we can conclude that causeways likely cause significant and potentially harmful genetic changes to fish species in Lake Champlain akin to dams in rivers.

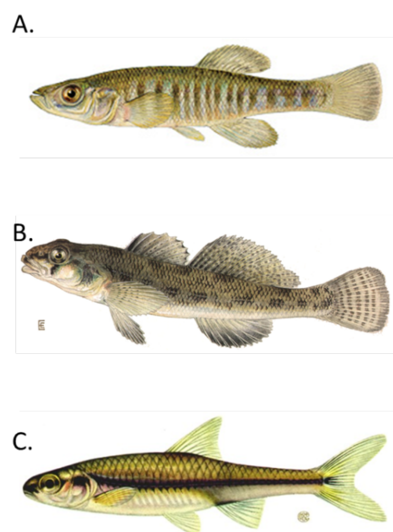

Figure 3: Potential study species: A) banded killifish B) tessellated darter C) bluntnose minnow.

We will test our hypotheses using molecular techniques on a single species present upstream and downstream of barriers in one or more rivers and in multiple basins in Lake Champlain. We initially identified three species that could fit this requirement: banded killifish (*Fundulus diaphanous*), tessellated darters

(*Etheostoma olmstedi*), or bluntnose minnow (*Pimephales notatus*) (Figure 3). We will choose a species based on availability of samples. By collecting fish across a range of fragmentation regimes, we will be able to determine differences in genetic structure and population demography such as heterozygosity, effective population size, and allelic richness among barrier types.

Once we have determined the genetic make-up of each population, we will be able to compare observed population structure among fragmentation pressures to determine how similar the fragmentation caused by causeways is to dam or natural fragmentation. We will be able to estimate migration and thus permeability of each barrier type, providing a comparable estimate of fragmentation impact. Additionally, grounding fragmentation analysis by using a known barrier type (dams) we will be able to infer how lake fragmentation might manifest in other systems. By understanding the extent of causeway fragmentation impacts, we will be able to inform management choices about potential causeway removal or construction.

Understanding the differences between river and lake habitat fragmentation will advance aquatic fragmentation research as a field by providing a contrast to dam fragmentation. Through the comparison of fragmentation impact with other types of fragmentation, the effect size of observed population changes can be better interpreted. For example, the population structure we observe in the lake could be similar to what we might expect in systems where fragmentation is partial (e.g., rivers with up and downstream fish passage). This work will also indicate whether further research is needed on water quality changes resulting from causeways, if such changes stimulate or repel movement of fishes between isolated basins.

16. Nature, scope, and objectives of the project including a timeline of activities

Nature: Research project aimed at quantifying the extent and history of the genetic impacts of fragmentation in Lake Champlain and the surrounding watershed.

Scope: A complete assessment of the genetic population structure of a model fish species across three different historical fragmentation pressures; geological, riverine dams, and lake causeways.

Objectives:

1) Quantify the genetic structure of fish species to determine the differences among populations separated by three types of fragmentation barriers.
2) Based on observed population structure, calculate a relative effect size of lake fragmentation by causeways compared to two types of river fragmentation

Timeline:

Fall 2015
- Prepare and plan for sampling.
- Begin sampling of rivers and lake to identify best study species.

Spring 2016
- PCR optimization on genetic markers.
- Begin sample collection.

Summer 2016
- Complete collection of samples.
- Begin genotyping.

Fall 2016
- Complete all genotyping.
- Begin data analysis.

Winter 2016/17
- Finish data analysis.
- Write manuscript and grant report.

Spring 2017
- Submit manuscript to peer reviewed journal.
- Attend professional conferences to present results.

17. Methods, procedures and facilities

Laboratory methods:

Fish will be sampled from sites in the Main Lake, Malletts Bay and the Northeast Arm of Lake Champlain (4 sites total), above and below dams in the Winooski and Lamoille rivers (4 sites total), and above and below the fall line in the Winooski and Lamoille rivers (4 sites total) using a combination of beach seining and backpack electrofishing. A target number of 30 - 50 fish will taken from each site and will be sacrificed in the field and returned to the laboratory on ice for work-up. In the laboratory, each fish will be measured to the nearest millimeter and sexed. Clips from the caudal fin of each fish will be taken and dried on blotting paper according to LaHood et al. (2008) for DNA extraction. DNA from clips will be extracted using a Qiagen Blood and Tissue Extraction Kit and amplified using polymerase chain reaction in the Wargo laboratory at the University of Vermont. Samples will then be multiplexed for 7-10 microsatellite markers in the DNA Analysis Core Facility at the University of Vermont and then and genotyped using GENEMAPPER (Applied Biosystems). Microsatellite markers will be taken from published sources and have been reported for all of the species likely to be used in this study (DeWoody et al. 2000; Rey & Turgeon 2007; Landis et al. 2009).

Data analysis:

Observed and expected heterozygosity and deviations from Hardy Weinberg equilibrium (HWE) will be calculated using the latest version of GENEALEX. Any loci found to not be under HWE will be removed from analysis. Spatial patterns of structure will be evaluated using F statistics calculated using FSTAT and ARLEQUIN. To determine if the Champlain region population sub-divides into distinguishable groups we will use an admixture-sensitive STRUCTURE analysis to determine the most probable number of groups present. This analysis will be conducted across all populations, as well as for each different type of barrier, to determine overall structure. Migration among sites and across barriers will be determined using BAYESASS. As a validation of our presumption that causeways and dams are barriers, we will use BIMr and BARRIER measure migration rates and identify barriers to confirm that some our barriers are detectable. To determine an effect size of causeway fragmentation, the degree of genetic separation between basins will be compared to the degree of genetic separation across dams and fall line populations. The amount of migration will also be compared as an estimate of the permeability of each barrier.

Facilities:
All research will take place at the University of Vermont. Field work will be conducted using university research vessels or a backpack electroshocker (Marsden laboratory). All fish processing will take place at the Rubenstein Ecosystem Science Laboratory. Molecular processing and analysis will take place in the Wargo laboratory in Stafford Hall which has the necessary facilities for all handling and analysis of molecular samples. Genotyping will be conducted in the DNA Analysis Core Facility located on campus.

18: Findings:

In spring and summer 2016, tessellated darters were collected from Lewis Creek, Missisquoi River, Indian Brook and three basins of Lake Champlain (Inland Sea, Malletts Bay, and the Main Lake). Sample sites within each area were chosen within 2.0 km of a barrier (dam, fall line, or causeway). A total of 677 tessellated darters was collected from 16 sites (Table 1). Sample rivers ranged in overall size (mean discharge 0.5 to 35.0 $m^3 s^{-1}$), barrier height, and barrier age (Table 2). Dams and causeways were built between 1797 and 1980 while both waterfalls were assumed to be approximately 12,000 years old. Height has not been accurately measured for waterfalls, however at the time of sampling each fall line was visually determined to be impassible to tessellated darters by having a visible drop of at least 0.5 – 1.0 m (Figure 4).

Table 1: Sample site locations and number of tessellated darters collected from the Lake Champlain basin.

Site	Lat	Lon	Number of Samples
Indian Brook Above Dam	44.513	-73.128	48
Indian Brook Above Dam Below FL	44.515	-73.131	24
Indian Brook Below Dam	44.543	-73.153	54
ISSR	44.635	-73.265	40
Lewis Above Dam 1	44.278	-73.176	50
Lewis Above Dam2	44.282	-73.173	42
Lewis Above Fall line 2	44.265	-73.205	63
Lewis Below dam 1	44.277	-73.182	22
Lewis Below dam 2	44.278	-73.177	56
Lewis Below Fall line	44.260	-73.213	35
Lewis Below Fall line	44.247	-73.231	29
Malletts-side of bike causeway	44.558	-73.304	43
Miss Above Dam	44.906	-73.106	55
Miss. Below Dam	44.921	-73.126	50
Sandbar-Malletts	44.630	-73.265	53
Sunset Isle	44.564	-73.319	13

Table 2: Summary of physical characteristics of barriers (dams, fall lines (FL) and causeways (CW) being compared for relative impacts on population genetic structure of tessellated darters.

Barrier name	Lat	Lon	Type	yr. built	Years since isolation	Height (m)	Mean stream discharge (m^3 s^{-1})
Lewis Creek FL	44.260	-73.213	Fall line	NA	12,000	NA	3.1
Lewis Creek Dam	44.279	-73.177	Dam	1980	37	3.96	3.1
Indian Brook FL	44.515	-73.128	Fall line	NA	12,000	NA	0.5
Indian Brook Dam	44.542	-73.153	Dam	1900	117	3.65	0.5
Missisquoi Dam	44.921	-73.128	Dam	1797	97	5.79	35.0
Outer Malletts CW	44.565	-73.311	CW	1899	98	0	NA
Sandbar CW	44.631	-73.256	CW	1850	167	0	NA

To date, nine microsatellite loci have been optimized for genotyping tessellated darters. In a preliminary analysis, 99 individuals from four sampling locations were genotyped at all nine loci. The four locations chosen were above and below the Lewis Creek fall line and above and below the Missisquoi River dam. These four sample sites were chosen to encompass two barrier types and a broad geographical separation (over 80 km). Three of the nine loci were monomorphic and therefore dropped from future analysis. The remaining six loci had 3 to 14 alleles and the overall observed heterozygosity across all individuals and loci was 0.48 (Table 3).

Table 3: Sample size (N,) sample size following removal for missing data (N'), number of different alleles (Na), number of effective alleles (Ne), informative index (I), observed and expected heterozygosity (Ho and He), unbiased expected heterozygosity (uHe) and fixation index (F) for 99 tesselated darters genotyped at six microsatellite loci.

	N	N'	Na	Ne	I	Ho	He	uHe	F
Lewis Above FL	24	20.500	3.667	1.813	0.710	0.344	0.385	0.395	0.065
Lewis Below FL	24	18.500	3.500	2.057	0.787	0.441	0.439	0.452	0.006
Miss Above Dam	24	14.000	5.000	3.174	1.141	0.524	0.574	0.594	0.064
Miss Below Dam	27	25.667	6.500	3.207	1.255	0.635	0.604	0.616	-0.052

Population differences

The most isolation of tessellated darter populations was among rivers (mean Fst = 0.13). However, pairwise comparisons of populations within a river, separated by a barrier, also showed signs of weak isolation (mean Fst = 0.015). There does not appear to be an obvious difference in amount of isolation resulting from dams when compared to fall line (Fst = 0.015 and 0.016). Diversity (observed heterozygosity and alleic richness) varied by river and in relation to barrier (Table 3). Tessellated darter populations in the Missisquoi River had higher heterozygosity than Lewis Creek. Additionally, heterozygosity was higher in populations downstream

Figure 4: Fall line at Lewis Creek sample site.

of a barrier compared to populations upstream of a barrier. Number of alleles was also higher in the population below the dam in Missisquoi river, but the number of alleles was slightly higher above the fall line in Lewis Creek.

19. Discussion

Samples were collected from all sites necessary for a complete assessment of the influence of barrier type on genetic structure of tessellated darters. The sampling locations spanned approximately 100 km along Lake Champlain’s eastern shore, providing a large-scale assessment of tessellated darter populations. Sample sites varied in size from a large river (Missisquoi River) to a relatively small tributary (Indian Brook). This diversity among sites allows evaluation of the impact of habitat fragmentation relative to river size. Sampling locations were also chosen with a wide range of barrier age (37 to 220 years old) which, when compared to fall lines, will allow us to test the hypothesis that barrier age has a significant impact on the resulting population structure.

Though the sample size of genotyped individuals is still small, preliminary analysis suggests that diversity of chosen microsatellite loci contain similar or slightly less diversity to previous microsatellite studies with other darter species in similar systems, suggesting that loci will be informative of population diversity and structure (Beneteau et al., 2009). Additionally, observed population differences partially support two of our hypotheses. First, the large difference between the first two rivers analyzed supports an underlying isolation by distance hypothesis of population structure. This is not surprising, given past work with other species of darters that has found large genetic differences between tributaries and evidence of isolation by distance (Roberts et al., 2013). Second, lower heterozygosity above stream barriers supports the hypothesis that river barriers are unidirectional, resulting in a reduction of upstream gene flow (Whiteley et al., 2010). Though a similar relationship for number of alleles was only noted in the Missisquoi River, the addition of more samples and could change this pattern. The lack of difference in Fst between the Missisquoi dam and Lewis Creek fall line does not support our hypothesis that barrier age is correlated with genetic structure. This could be due to relatively free down-stream movement of darters across both fall lines and dams, allowing for enough population connectivity to reduce long-term genetic effects. Alternatively, the lack of genetic structure could suggest that the fall line is a weaker barrier to upstream migration than the Missisquoi dam, reducing the observed genetic structure between populations upstream and downstream of the fall line. The ability to identify differences in genetic diversity and structure between rivers and across barrier types with less than 100 individuals and only six loci suggests that our current goal of 500 individuals and 10 – 12 loci should be sufficient to robustly test our hypotheses.

To complete the present study, several analyses and field collections are still needed. First, four additional microsatellite loci need to be identified and optimized for genotyping tessellated darter samples. Following the successful identification of a panel of 10 to 12 microsatellite loci, 30 to 50 individuals from at least three sites in each of our sampling locations will be genotyped and genetic structure will be analyzed. Finally, a manuscript describing our results and comparison of barrier-specific influences will be submitted for publication in a peer reviewed journal with a focus on conservation genetics and habitat fragmentation.

Habitat fragmentation – Lake Champlain

Habitat fragmentation in Lake Champlain has recently received increasing interest. A review of the history of Lake Champlain suggested that both riverine and lake habitat fragmentation could be impacting fish spawning and movement in the Champlain basin (Marsden & Langdon 2012). This led to a more intensive study assessing the genetic structure of lake whitefish in Lake Champlain (Parent, Marsden et al. *unpublished data*). Currently, funding from the Great Lakes Fishery Commission is being used to develop an acoustic telemetry program to assess lakewide movement of fish populations and evaluate genetic structure of several species. Acoustic telemetry is being used to monitor walleye movement through causeway openings; genetic research of the impact of causeways on rainbow smelt and slimy sculpin populations in the different basins of Lake Champlain is ongoing. The GLFC grant will help support fall and winter funding for the graduate student working on the proposed project and contribute to additional costs of the resources needed to complete the project.

Habitat fragmentation – conservation management

Habitat fragmentation is common conservation issue in aquatic systems. According to the Army Corps of Engineers there are approximately 87,000 dams in the United States. When rivers become fragmented by dams, the aquatic habitat is changed through sedimentation and changes in hydrology (Bunn & Arthington 2002) and the movement of fish is constrained (Meldgaard et al. 2003). The fragmentation of rivers has been extensively studied and its ecological and genetic impacts on local fish communities is well characterized (Ligon et al. 1995). Much of the historic research on habitat fragmentation has focused on the large impact dams have on anadromous fishes of commercial interest, such as salmonids (Neraas & Spruell 2001; Morita & Yamamoto 2002) and sturgeon (Braaten et al. 2015). Many other studies have attempted to determine the impact that habitat fragmentation has on non-migratory fish such as sculpins (Baumsteiger & Aguilar 2014) and suckers (Bessert & Orti 2008). The discovery that dams were likely the cause for large declines in Pacific salmon populations in the Pacific Northwest led to the installment of fish passage systems with moderate success (Noonan et al. 2015) and fish passage around dams continues to be a central issue in western rivers. In the Great Lakes, dams pose both a threat to potamodromous fish such as lake sturgeon (Auer 1996), and a management benefit by helping with control of invasive species (Lavis et al. 2003). However, current research largely focuses on fish movement within rivers fragmented by dams, with little research addressing lake fragmentation and isolation.

Habitat fragmentation is also a concern for endangered species. The construction of barriers can cause local habitat degradation and changes in habitat size and quality by increasing rates of sedimentation below dams or inundating large areas of habitat through the construction of reservoirs (Ligon et al. 1995; Wang et al. 2010). These habitat alterations can have serious implications for threatened or endangered species. Additionally, dams and other manmade structures often impact spawning by affecting water regimes (Bessert & Orti 2008) or blocking fish from reaching preferred spawning habitat altogether (Neraas & Spruell 2001). Fragmentation isolates small populations, making them more vulnerable to local extinction (Macarthur & Wilson 1967; Templeton et al. 1990).

Habitat fragmentation – genetics

A major concern of habitat fragmentation is the impact it has on the genetic structure of populations. By limiting migration among sub-populations, fragmentation can lead to decreased gene flow and increased inbreeding, weakening the ability of populations to adapt to change (Templeton et al. 1990). Over time, populations separated by barriers do show genetic divergence (Morita & Yamamoto 2002), sometimes leading to phenotypic differences within populations (Brodersen et al. 2015). However, it is difficult to determine whether current fragmentation in a given habitat will lead to enough genetic divergence and inbreeding to become a concern. The majority of genetic fragmentation analysis has focused on large-bodied anadromous fish, although some studies have also been conducted on smaller-bodied or stream-resident fish species such as sculpin (*Cottus spp.*), bullhead (*Cottus gobio*), suckers, log perch (*Percina caprodes*), and greenside darters (*Etheostoma blennioides*). For example, dams were found to impact the dispersal of bullhead in the Sense River, Switzerland, leading to detectable genetic structure throughout the river system (Junker et al. 2012). In other systems, dams were not found to significantly impact the distribution or genetic structure of common resident species such as sculpin (Baumsteiger & Aguilar 2014) or log perch and greenside darters (Haponski et al. 2007). End with a sentence or two re-interating how your study contributes to this body of knowledge

20. Training potential:

Our proposed project has further developed the research skills of Peter Euclide, a PhD student in the Biology Department at the University of Vermont. Additionally, Peter was able to train and supervise two undergraduate researchers who helpped conduct all of the field sampling and some of the laboratory work. The project will yield a manuscript to submit to a peer reviewed journal and act as a chapter of a PhD dissertation.

21. Investigator qualifications (following pages**)**

PETER T. EUCLIDE

Department of Biology, University of Vermont
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peuclide@uvm.edu

EDUCATION

University of Vermont, Burlington, Vermont
M.Sc. in Natural Resources (Aquatic Ecology and Watershed Science), Jan 2015
Kent State University, Kent, Ohio
BS in Organismal Biology, 2012

RESEARCH EXPERIENCE

Graduate Research Assistant: PhD. Dissertation, Effect of human-caused habitat fragmentation on fish genetic diversity. 2014-present
Graduate Research Assistant: M.Sc. Thesis, Fixed versus plastic partial migration of the aquatic macroinvertebrate, *Mysis diluviana*, in Lake Champlain. 2012-2014
Graduate Research Assistant: Literature assessment of population declines of *Mysis diluviana* in the Great Lakes. 2013-present
Undergraduate Research: Winter decomposition rates of forest leaf litter associated with fungal and invertebrate diversity. 2012
Undergraduate Research Assistant: population genetics and the evolution of variable sex ratios in populations of *Lobelia siphilitica.* 2011-2012
Undergraduate Research: Macroinvertebrate community ecology of in stream leaf packs. 2009-2012
Undergraduate Research Assistant: Bacterial community composition and colonization of crayfish in northeastern Ohio streams. 2010
Undergraduate Research: Distribution and diversity of meadow insects. 2010
Research Field Technician: Collection and use of milfoil weevil as a biological control for Eurasian milfoil in Michigan and Canada. 2009

PUBLICATIONS

Euclide, PT, Stockwell, JD. 2015. Effect of gut content on $\delta^{15}N$, $\delta^{13}C$, and C:N of experimentally-fed *Mysis diluviana*. Journal of Great Lake Research. 41: 926-929.
Add sculpin paper in review

DATA PUBLICATIONS

Lake Champlain Mysis Stable Isotopes. KNB. https://knb.ecoinformatics.org/#view/knb.749.1

GRANTS and AWARDS

ASLO Student Travel Grant: $500, January 2014
Lintilhac Foundation Research Grant: $10,000, January 2014

Graduate Student Senate Travel Grant: $300, October, 2013
Rubenstein Graduate Student Association Mini-Grant: $200, October 2012 and December 2013
Grant awarded by the University of Vermont Graduate Student Association to pay for lab supplies

RESEARCH PRESENTATIONS (Presenter underlined)

Euclide, P.T., Parent, T., Gonzalez, E., Flores, N., Wargo, M., Kilpatrick, C.W., Marsden, J.E. Effect of Fish Dispersal Ability on Sensitivity to Habitat Fragmentation in a Large Lake. 2015 American Fisheries Society. Portland, Oregon [oral presentation]
Euclide, P.T., Strayer, N., J.D. Stockwell. 2013. Is *Mysis* in decline in the Laurentian Great Lakes? 2015 International Association of Great Lakes Research 2015 meeting. Burlington, Vermont [poster]
Euclide, P.T., J.D. Stockwell. 2013. Fixed versus plastic partial migration of the aquatic macroinvertebrate, *Mysis diluviana*, in Lake Champlain. 2014 Joint Aquatic Sciences Meeting. Portland, Oregon [poster]
Euclide, P.T., J.D. Stockwell. 2013. Physiological plasticity in the diel vertical migration of *Mysis diluviana* . RSENR Graduate Student Research Symposium, Vermont [oral presentation]
Euclide, P.T., J.D. Stockwell. 2013. Physiological plasticity in the diel vertical migration of *Mysis diluviana* . University of Vermont Student Research Conference, Vermont [oral presentation]
Euclide, P.T., J.D. Stockwell. 2013. Physiological plasticity in the diel vertical migration of *Mysis diluviana* . 2013 Lake Champlain Research Consortium Student Symposium [oral presentation]

TEACHING

Communicating Science REU Workshop: Summer 2015, University of Vermont
Communicating Science REU Workshop: Summer 2014, University of Vermont
Champlain Research Experience for Students and Teachers (CREST) Workshop Fellowship:
Summer 2014, University of Vermont
ECHO Lake Aquarium Educator Fellowship: Fall 2013-Fall 2014, University of Vermont and ECHO Lake Aquarium and Science Center
Facilitator of demonstration "Creatures of the Night, *Mysis"* and patron encounter "What are we catching?"
Teaching Assistantship: Limnology, Fall 2013, University of Vermont.
Teaching Assistantship: Ecology, Ecosystems and Environment, Spring 2013, University of Vermont
Teaching Assistantship: Limnology, Fall 2012, University of Vermont

PERTINENT SKILLS

Computer:
Statistical analysis using R, JMP, SPSS, and Past
Genetic analysis using Genemapper, and BLAST
Laboratory:
Genetic: DNA extraction, PCR, gel electrophoresis, microsatellite analysis
Stable Isotope: analysis and sample preparation
Eco-physiology: Blazka type swim-tunnel respirometry and swimming performance

J. ELLEN MARSDEN

Rubenstein School of Environment and Natural Resources, University of Vermont
308D Aiken Center, Burlington, VT 05405
802-656-0684 ellen.marsden@uvm.edu

RESEARCH INTERESTS

Great Lakes fisheries restoration and ecology; ecological effects of introduced species; lake trout early life history and spawning behavior; conservation of genetic resources in fisheries

EDUCATION

Ph.D. - Cornell University, Department of Natural Resources, 1988.
M.S. - Cornell University, Ecology & Systematics, 1985.
B.A. - Bryn Mawr College, Biology, 1978.

PROFESSIONAL EXPERIENCE

Professor, University of Vermont, since 2006; Chair, Wildlife and Fisheries Biology Program, 2012-2015

Associate Professor, University of Vermont, 2001 – 2006; Assistant Professor, 1996 - 2001

Associate Professional Scientist, Illinois Natural History Survey; Director, Lake Michigan Biological Station, 1990-96

RECENT GRANTS

2016 Kozel, C., and J. E. Marsden. Can early feeding ameliorate thiamine deficiency in wild lake trout fry? Water Resources Center – thiamine and fry - $10,000

2015 Marsden, J. E. Evaluation of successful lake trout recruitment in Lake Champlain: what has changed? UVM John Hilton faculty research fund, $10,151

2014 Marsden, J. E. and J. D. Stockwell. An acoustic telemetry array for Lake Champlain: investigating effects of aquatic habitat fragmentation on lake whitefish. Water Resources Center. $40,000

2014-2015 Marsden, J. E., J. Rinchard, and A. Evans. Can early feeding in lake trout fry ameliorate thiamine deficiency? Great lakes Fishery Commission. $138,977

2013-2018. Marsden, J. E. and J. D. Stockwell. Lake Champlain fish ecology: a mesocosm approach to the Great Lakes. Great Lakes Fishery Commission. $945,000.

2013-2014. Marsden, J. E., C. Guy, R. Gresswell. Evaluation of lake trout egg distribution, density, and survival in Yellowstone Lake. Wyoming Council of Trout Unlimited. $190,000

2012-2013 Marsden, J. E., J. Johnson . Attraction of spawning lake trout to conspecifics and reef odor. Great Lakes Fishery Commission $50,000

2011-2013. Marsden, J. E., W. Kilpatrick, and W. Ardren. Genetic examination of lake whitefish population sub-structuring among basins in Lake Champlain. State Wildlife Incentives Grant, VTDFW, $39,688

SELECTED PROFESSIONAL ACTIVITIES

Board of Technical Experts, Fisheries Research Board of the Great Lakes Fishery Commission, 2014 - present

Sea Lamprey Research Board, Great Lakes Fishery Commission, 2003-2012 (Chair 2005 – 2010)

Lake Champlain Basin Program Aquatic Nuisance Species Committee, 2005 - present
Lake Champlain Fisheries Technical Committee, 1997 - present

RECENT PUBLICATIONS

REVIEWED CHAPTERS

Marsden, J. E., P. Stangel, A Shambaugh. 2013. Zebra mussels in Lake Champlain: a sixteen-year monitoring database. Chapter 2, In: T. Nalepa and D. Schloesser, Quagga and Zebra Mussels: Biology, Impacts, and Control, 2nd ed. CRC Press.

Thurow, R. F., C. A. Dolloff, and **J. E. Marsden**. 2012**.** Visual observation of fish and aquatic habitat. Chapter 17, In: A. V. Zale, D. L. Parrish, and T. M .Sutton, eds., Fisheries Techniques 3rd ed., American Fisheries Society, Bethesda, MD.

REVIEWED JOURNAL ARTICLES (* indicates graduate student authors; ** undergraduate student authors)

Johnson' N. S, D. Higgs, T. R. Binder, **J. E. Marsden**, T. Buchinger, L. Brege, T. Bruning, S. Farha and C. C. Krueger. In press. Evidence of sound production by spawning lake trout (*Salvelinus namaycush*) in lakes Huron and Champlain. Can. J. Fish. Aquat. Sci.

Binder' T. R., J**. E. Marsden**, S. C. Riley, J. E. Johnson, N. S. Johnson, J. He, M. Ebener, C. M. Holbrook, R. A. Bergstedt, C. R. Bronte, T. A. Hayden, and C. C. Krueger. In press. Lake-wide movements and spatial segregation of two populations of lake trout, *Salvelinus namaycush*, in Lake Huron. J. Great Lakes Res.

Pinheiro*, V. M., J. D. Stockwell, and **J. E. Marsden**. 2016. Lake trout (*Salvelnus namycush*) spawing site use in Lake Champlain. J. Great Lakes Res. 00:00-00

Marsden' J. E., J. Johnson, J. He, N. Dingledine, J. Adams, T. R. Binder, N. Johnson and C. C. Krueger. 2016. Five-year evaluation of habitat remediation in Thunder Bay, Lake Huron: comparison of characteristics of constructed reefs that attract spawning lake trout. Fisheries Research 183:275–286

Ladago*, B. J., **J. E. Marsden**, and A. Evans. 2016. Could early feeding by lake trout fry mitigate thiamine deficiency? Trans. Am. Fish. Soc. 145:1-6

Marsden, J. E., H. Tobi**. 2014. Sculpin predation on lake trout eggs in interstices: skull compression as a novel foraging mechanism. Copeia. 2014:654-658 (received award for Best Paper of 2014)

Lochet, A, B. J. Fryer , S. A. Ludsin, E. A. Howe, and **J. E. Marsden**. 2014. Discriminating the natal origin of spawning adult sea lamprey (*Petromyzon marinus*): reevaluation of the statolith microchemistry approach. N. Am. J. Fish. Manage. 40:763-770.

Janssen, J., **J. E. Marsden**, T. R. Hrabik, and J. D. Stockwell. 2014. Are the Laurentian Great Lakes great enough for Hjort? ICES Journal of Marine Science. 71:2242-2252

Lochet, A., **J. E. Marsden**, B. J. Fryer and S. A. Ludsin. 2013. Instability of statolith elemental signatures revealed in newly-metamorphosed sea lamprey (*Petromyzon marinus*). Can. J. Fish. Aquat. Sci 70: 565-573

Herbst*, S. J., **J. E. Marsden**, and B. J. Lantry. 2013. Lake whitefish diet, condition, and energy density in Lake Champlain and the lower four Great Lakes following dreissenid invasions. Trans. Am. Fish. Soc. 142:388-398

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Baumsteiger J, Aguilar A. 2014. Impact of dams on distribution, population structure, and hybridization of two species of California freshwater sculpin (*Cottus*). Conservation Genetics 15:729-742.

Beneteau, C. L., Mandrak, N. E., & Heath, D. D. 2009. The effects of river barriers and range expansion of the population genetic structure and stability in Greenside Darter (*Etheostoma blennioides*) populations. Conservation Genetics, 10: 477–487.

Bessert ML, Orti G. 2008. Genetic effects of habitat fragmentation on blue sucker populations in the upper Missouri River (*Cycleptus elongatus* Lesueur, 1918). Conservation Genetics 9:821-832.

Braaten PJ, Elliott CM, Rhoten JC, Fuller DB, McElroy BJ. 2015. Migrations and swimming capabilities of endangered pallid sturgeon (*Scaphirhynchus albus*) to guide passage designs in the fragmented Yellowstone River. Restoration Ecology 23:186-195.

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Brodersen J, Howeth JG, Post DM. 2015. Emergence of a novel prey life history promotes contemporary sympatric diversification in a top predator. Nature Communications 6.

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Facey, DE, Marsden JE, Mihuc TB, Howe EA. 2012. Lake Champlain 2010: A summary of recent research and monitoring initiatives. Journal of Great Lakes Research 38: 1–5.

Fahrig L. 1997. Relative effects of habitat loss and fragmentation on population extinction. Journal of Wildlife Management 61:603-610.

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Fortin N, Munoz-Ramos V, Bird D, Lévesque B, Whyte LG, Greer CW. 2015. Toxic cyanobacterial bloom triggers in Missisquoi bay, Lake Champlain, as determined by next-generation sequencing and quantitative PCR. Life (Basel, Switzerland) Multidisciplinary Digital Publishing Institute 5: 1346–1380.

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Levine, S. N., Lini A., Ostrofsky ML, Bunting L, Burgess H, Leavitt PR, Reuter D, Lami A, Guilizzoni P, Gilles E. 2012. The eutrophication of Lake Champlain’s northeastern arm: Insights from paleolimnological analyses. Journal of Great Lakes Research 38: 35–48.

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Neraas LP, Spruell P. 2001. Fragmentation of riverine systems: the genetic effects of dams on bull trout (*Salvelinus confluentus*) in the Clark Fork River system. Molecular Ecology 10:1153-1164.

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Roberts, J. H., Angermeier, P. L., & Hallerman, E. M. 2013. Distance, dams and drift: What structures populations of an endangered, benthic stream fish? Freshwater Biology, 58: 2050–2064.

Templeton AR, Shaw K, Routman E, Davis SK. 1990. The genetic consequences of habitat fragmentation. Annals of the Missouri Botanical Garden 77:13-27.

Trombulak SC, Frissell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14:18-30.

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Whiteley, A. R., Hastings, K., Wenburg, J. K., Frissell, C. A., Martin, J. C., & Allendorf, F. W. 2010. Genetic variation and effective population size in isolated populations of coastal cutthroat trout. Conservation Genetics, 11: 1929–1943.

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Impacts of climate change on winter-spring transition in plankton communities

Basic Information

Title:	Impacts of climate change on winter-spring transition in plankton communities
Project Number:	2016VT82B
Start Date:	3/1/2016
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	Vermont-at-Large
Research Category:	Biological Sciences
Focus Category:	Ecology, Nutrients, Surface Water
Descriptors:	None
Principal Investigators:	Jason D. Stockwell, Allison Hrycik

Publications

There are no publications.

13. Title: Impacts of climate change on winter-spring transition in plankton communities

14. Statement of regional or state water problem.

Mounting evidence suggests that winter dynamics play an important role in the composition and condition of aquatic communities during the growing season[1]. Winter, however, has received very little attention in limnology because of logistical constraints[2] and the assumption that winter is an insignificant and static time[3,4]. As duration of ice cover decreases[5] and precipitation patterns are altered[6] by climate change, the need to understand winter food web and plankton community dynamics and their impacts on ecosystems and ecosystem services later in the year has become increasingly evident[3,4]. Our proposed research will broaden our understanding of winter-spring transition in plankton communities by testing hypotheses about (1) effects of weather on under-ice food webs via light limitation and (2) trends in plankton community composition during the winter-spring transition and their implications for predicting summer cyanobacteria density.

Nutrient limitation is a main driver of plankton growth and community composition during the open water season[7,8], but may become secondary to light limitation during the winter. Even small changes in ice cover and snow depth can drastically limit the amount of photosynthetically active radiation (PAR) that is available to autotrophs under the ice[9]. The decrease in PAR translates to observable differences in the phytoplankton community, with the most abundant groups in winter being those that possess adaptations to low-light environments such as movement ability and capacity for mixotrophy[10–15]. In this study, we will compare two lakes considered to be hyper-eutrophic during the summer: Shelburne Pond and Missisquoi Bay, Lake Champlain. Phytoplankton communities in both lakes are dominated by cyanobacteria during the summer and early fall[16,17]. Preliminary data indicate that the two lakes are strikingly different in phytoplankton and zooplankton production during the winter (Fig. 1), suggesting a mismatch in drivers of summer and winter trophic relationships and system productivity. Our research will experimentally test the effects of decreased snow accumulation in the northeastern US on winter plankton community composition and food web dynamics as light levels are altered by climate change.

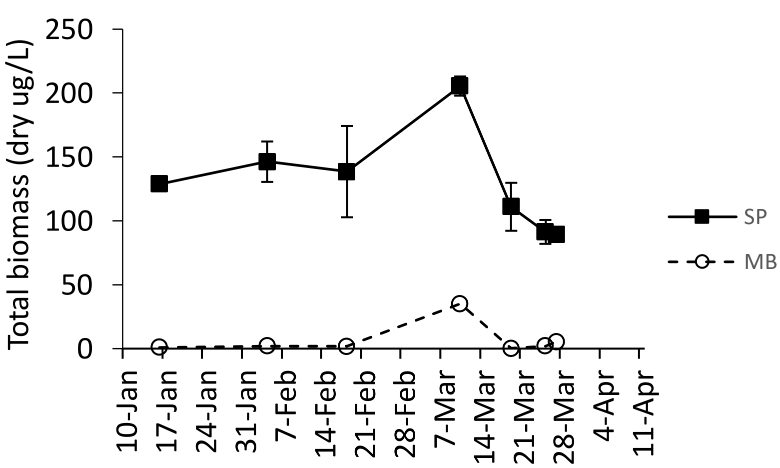

Fig. 1. *Zooplankton biomass in Shelburne Pond (SP) and Missisquoi Bay, Lake Champlain (MB) during the winter of 2014 (J. Stockwell, unpublished data).*

Beyond the importance of understanding the dynamics of an under-studied season, knowledge of winter limnology may inform predictions about the subsequent ice-free season, including magnitude of cyanobacteria blooms. Cyanobacteria can produce toxins that are harmful to humans, pets, and wildlife[18,19], have increased over time[20], and are expected to continue to increase into the future[21,22]. Cyanobacteria blooms are heavily influenced by the amount of available nutrients[23,24], which are affected by temperature and ice cover throughout the winter[25]. Many models for cyanobacteria forecasting have low predictive power due to importance of site-specific factors[26], and one missing but important link may be site-specific inoculum concentrations of cyanobacteria that emerge from winter conditions. Severity of winter conditions influence the proportion of cyanobacteria present in the early spring. Winters with shorter ice-cover duration promote increased proportion of cyanobacteria in lakes[27,28]. Inoculum conditions in the water column[28] and sediment[29] set the stage for the magnitude of summer cyanobacteria blooms[28].

Understanding the influence of winter conditions on plankton communities and their implications for changing conditions in the future will be of great interest to several stakeholder groups in Vermont, including residents, visitors, and municipalities. Burlington and several other Vermont municipalities obtain their drinking water directly from Lake Champlain, which experiences cyanobacteria blooms in some of its shallow bays[16,30]. Filtering out cyanotoxins and cyanobacteria in water treatment plants can be a complex, multi-point process[31], and when performed insufficiently, may result in municipal water sources that are unsafe to drink[32]. In addition to concerns over drinking water, local residents may have a mismatch in management objectives with Lake Champlain managers. In a study to examine public management preferences for Lake Champlain, stakeholders ranked issues related to harmful algal blooms as high priorities, including fish toxicity, water clarity, and beach closures, despite current management focus on nutrient management[33]. Although these factors are interrelated, this study revealed a disparity between perceived priorities of lake managers and those of recreational lake users, indicating a public preference for increased focus on water management issues related to visible algal blooms. In the context of our proposed study, additional and novel information about the potential drivers of cyanobacterial blooms will allow earlier, more accurate prediction of blooms, with more time possible for potential mitigation measures.

Harmful algal blooms (HABs) including cyanobacteria and other algae[27] negatively impact economies through lost revenues from recreation and tourism as well as decreased property values. Tourism is a staple industry in the region, with tourist spending accounting for approximately 14% of Vermont's state output[29]. HABs reduce property values by making shoreline property less desirable[34]. These problems are prevalent in Vermont, as evidenced by several beach closures per year due to high levels of cyanotoxins[35] and major reductions in property values along areas of Lake Champlain that have been impacted by HABs[36]. HABs occur frequently in many shallow lakes in Vermont, including our study sites of Missisquoi Bay, Lake Champlain[16,30] and Shelburne Pond[17].

Sport fishing is also an important economic activity in Vermont[37]. Increased knowledge of winter conditions and subsequent algal blooms will allow us to better understand how sport fish may interact with plankton communities during the winter, and to better anticipate what conditions they may encounter later in the growing season. Many local stakeholders support tracking toxicity in fish as a management goal in Lake Champlain[33], which may be influenced by cyanotoxins under extreme conditions[38]. More commonly, however, sport fish are affected by hypoxic conditions caused by HABs that may lead to decreased growth[39–41], decreased consumption[42–44], impaired reproduction[45], or fish kills[46].

15. Statement of results or benefits.

Understanding trophic relationships under ice will contribute to our knowledge of how changes in winter temperatures and precipitation affect freshwater ecosystems to inform policy on anthropogenic nutrient loading and climate change. Furthermore, a quantitative link between winter conditions and subsequent phytoplankton community composition will provide earlier, more informed predictions of cyanobacteria blooms. Cyanobacteria blooms represent a serious public health risk[19] that have gained increasing public attention[32], especially related to a recent high-profile drinking water ban in Toledo, Ohio[32]. Several studies have linked ambient temperature and nutrient conditions to cyanobacteria abundance[23,24,26] or demonstrated relationships between winter conditions and early spring phytoplankton communities[27,28], but none have directly tested the effects of light limitations and grazing rates on phytoplankton density and community composition *in situ*.

Most Vermont residents use local lakes recreationally or as a drinking water source, and thus are invested in maintaining thriving lake ecosystems that can provide necessary ecosystem services. An integral part of this study is the dissemination of information (detailed below) that will increase awareness of the implications of climate change on winter limnology and the subsequent impacts on inoculum conditions of cyanobacteria following spring turnover. By disseminating information through several outlets including Lake Champlain Sea Grant and the ECHO Lake Aquarium and Science Center in Burlington, VT, we expect to reach a diversity of residents who use Vermont lakes recreationally, as water sources, or as indirect revenue sources through tourism.

16. Nature, scope, and objectives of the project, including a timeline of activities.

We propose to test the drivers of winter plankton community dynamics to provide insight into how winter precipitation patterns influence inoculum conditions of plankton communities in the early spring. We will accomplish this using a mesocosm study to assess the changes in winter plankton communities under the influence of altered PAR transmission. We will perform baseline measurements and mesocosm experiments during January through April, 2016, with weekly follow-up monitoring throughout the remainder of the year. Data analysis and write-up will occur during the summer of 2016. We will disseminate information through professional organizations, Lake Champlain Sea Grant, and ECHO Lake Aquarium and Science Center from September through December, 2016.

17. Methods, procedures, and facilities.

We will conduct under-ice grazing experiments in suspended enclosures in Shelburne Pond and Missisquoi Bay following standard experimental methods that have primarily been used during the ice-free season[47]. We will assemble enclosure experiments in a full-factorial design to test two lakes, five zooplankton grazer densities, and two light levels (Fig. 2) with two replicates per treatment combination. Enclosures will consist of 10-L transparent carboys filled with lake water and ambient phytoplankton. We will filter out zooplankton then re-introduce five specific densities: no zooplankton, half of natural density, natural density, twice natural density, and ten times natural density. These manipulated zooplankton densities will mimic what we would expect in lakes with varying amounts of fish predation on zooplankton, and will include extremes from no zooplankton to ten times natural density to explore extreme limits on ecosystem dynamics[48]. Fish predation may be an important driver of zooplankton and phytoplankton biomass during the winter[15,49]. However, winter planktivore abundances may be unpredictable because fish populations can also be influenced by winter conditions such as fish kills. In this study, we will simulate controlled levels of fish planktivory by altering zooplankton densities. We will modify the light environment by clearing snow from an area of each lake because snow cover affects PAR transmittance to a much higher degree than ice cover[9]. Enclosures will be suspended under the ice between two holes drilled with an auger using ice anchors. We will incubate enclosures for one week to adjust standard 72 hour incubations for slower phytoplankton growth rates at low temperatures[50,51]. Both sites experience sufficient ice cover for experiments from mid-December to mid-April, with ice thickness up to 1 m in recent years years.

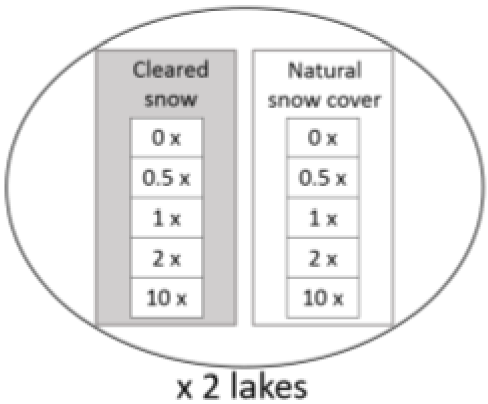

Fig. 2. *Experimental design to be replicated in Missisquoi Bay, Lake Champlain and Shelburne Pond. Numbers indicate zooplankton densities in relation to natural density.*

We will determine total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate, chlorophyll-a, snow depth, ice depth, temperature, under-ice PAR, dissolved organic carbon (DOC), particulate organic carbon (POC), and phytoplankton species composition, phytoplankton biovolume, zooplankton species composition, and zooplankton biomass before and after incubations. Measurements before incubations will be taken prior to snow removal, and all measurements will be taken concurrently in the water column as a control. In addition, we will install a thermistor string at each site to monitor temperature at 0.5m intervals under the ice. The Stockwell Lab is outfitted for under-ice limnology, with equipment such as augers, portable shanty labs, heaters, and ice sleds. Additionally, the Stockwell Lab has acquired a FlowCam for phytoplankton analysis, greatly increasing the speed at which samples can be processed.

We will analyze responses in continuous variables (total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate, chlorophyll-a, temperature, under-ice PAR, DOC, POC, total phytoplankton biomass, cyanobacteria biomass, and total zooplankton biomass) from mesocosm experiments using nested ANOVAs with grazer density and light treatments nested within site. Effects of light and zooplankton grazer densities on phytoplankton and zooplankton community composition will be analyzed using PERMANOVAs with Bray-Curtis distance for each lake.

We expect to see increased phytoplankton biomass and chlorophyll-a in trials where snow has been cleared, except under the highest zooplankton densities, indicating release from bottom-up control (i.e., light limitation). In addition, we expect that phytoplankton species with adaptions to low light levels such as movement ability and mixotrophy will lose competitive advantage and decline in relative abundance under release from light limitation. We expect that cyanobacteria in the mesocosms will remain at low levels but increase relative to baseline levels as light availability increases[27,28]. We do not expect to see changes in zooplankton biomass or community composition over one week.

Follow-up monitoring will occur every week throughout the year. We will measure the same parameters measured in mesocosm experiments (total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate, chlorophyll-a, snow depth, ice depth, temperature, PAR, DOC, POC, and phytoplankton species composition, phytoplankton biovolume, zooplankton species composition, and zooplankton biomass) on each sampling date. We will also measure phytoplankton species composition and biovolume in the benthos to assess the importance of sediment innocula of cyanobacteria. These parameters will become part of a larger data set that has been assembled in Shelburne Pond by the Stockwell Lab since 2014 and in Missisquoi Bay by the VT EPSCoR Research on Adaptation to Climate Change project since 2012. High-frequency sensor data (water quality and weather) from Shelburne Pond, which is part of the GLEON (Global Lake Ecological Observatory Network) network of monitoring buoys, and Missisquoi Bay will be concurrently collected. After several years of collection, these monitoring data will allow us to examine potential links between winter severity and magnitude of cyanobacteria blooms the following summer to test our expectation that increased inoculum conditions of cyanobacteria following less severe winters lead to increased magnitude of cyanobacteria blooms during the summer.

19. Findings

Full mesocosm experiments were not performed due to unusually warm winters in the 2015-2016 and 2016-2017 field seasons that created unsafe ice. However, we performed initial trials to test feasibility of mesocosm experiments, and are confident that we can run full experiments in the case of sufficient ice cover. We completed one preliminary mesocosm trial with two carboys deployed in Shelburne Pond for 6 days, and measured the ambient phytoplankton densities at the start of the experiment (representing initial conditions for mesocosms) as well as phytoplankton densities after six day incubations just under the ice. One mesocosm was stocked with ambient zooplankton grazer density (1x treatment), and the other was stocked with high zooplankton grazer density (10x treatment). Light was not manipulated in our preliminary trials. Initial phytoplankton samples displayed a great deal of variability, and the ambient zooplankton treatment had higher phytoplankton density than the high zooplankton treatment after the six-day incubation period, although relative proportions of major phytoplankton groups remained consistent with dominance of cryptophytes, followed by diatoms (Fig. 3).

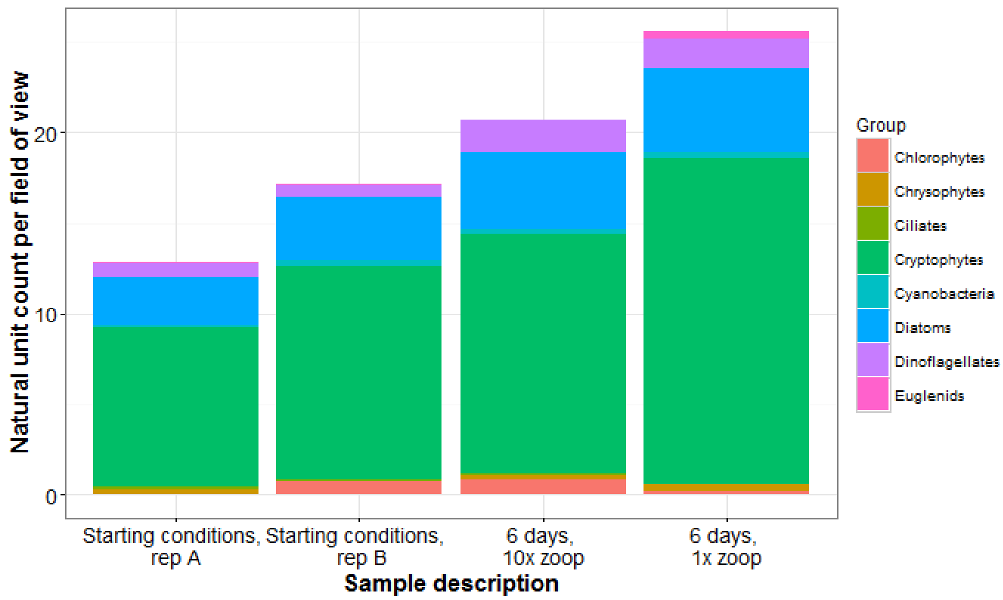

Fig 3. *Relative numbers of phytoplankton groups from ambient conditions in Shelburne Pond before mesocosm experiments (first two bars) and after 6 days with either 10x natural zooplankton density (third bar) or ambient zooplankton density (fourth bar). Relative numbers are given in terms of natural units (i.e., a single cell is counted for species that are obligately single-celled, and a colony is counted for species that form cohesive colonies).*

Shelburne Pond sampling continued every week during the ice-free season and every other week during ice cover when ice was safe for sampling. This sampling is still in progress, but initial data provide insights into winter and spring dynamics in Shelburne Pond. Colder air temperatures in the winter of 2014-2015 were associated with a long period of ice cover and an inverse stratification pattern under ice, with colder temperatures near the top of the water column. Warming in the spring was evident under ice just prior to ice break-up (Fig. 4). A warmer winter in 2015-2016 was associated with a shorter period of ice cover, and a nearly isothermal water column, with a distinct warming trend leading to ice-out (Fig. 4). Temperature data from winter 2016-2017, which was uncharacteristically warm, will be downloaded in the coming weeks.

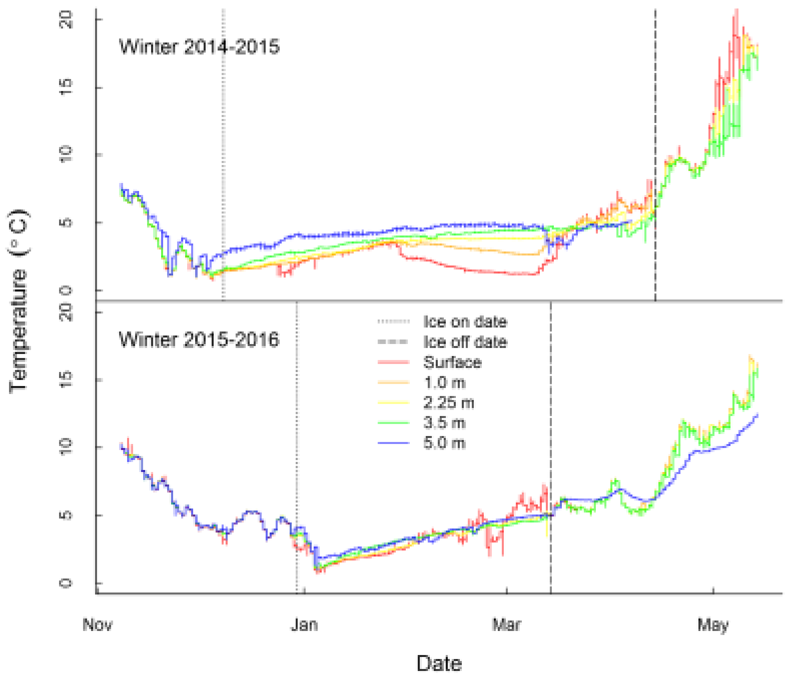

Fig. 4. *Water temperatures from temperature loggers deployed in Shelburne Pond through the winter of 2014-2015 and 2015-2016. Winter 2014-2015 was characterized by record cold temperatures and thick ice, while winter 2015-2016 was characterized by warm temperatures and a relatively brief period of ice cover. Some data loggers malfunctioned, and are therefore not graphed for the entire duration of the study.*

We also analyzed zooplankton samples from under the ice and just after ice melt in the spring from both years represented by continuous temperature monitoring. This sub-set of the project was completed in the summer of 2016 by REU student Shannon McFarland as part of our winter limnology study during the duration of this grant. The colder winter saw cyclopoid copepods persist in high numbers throughout the winter, with a dramatic increase in *Daphnia* and other cladoceran zooplankton in the spring (Fig. 5). During the warmer winter, more zooplankton taxa persisted during ice cover, and cyclopoid copepods peaked just after ice-out, while *Daphnia* peaked later in the spring (Fig. 5).

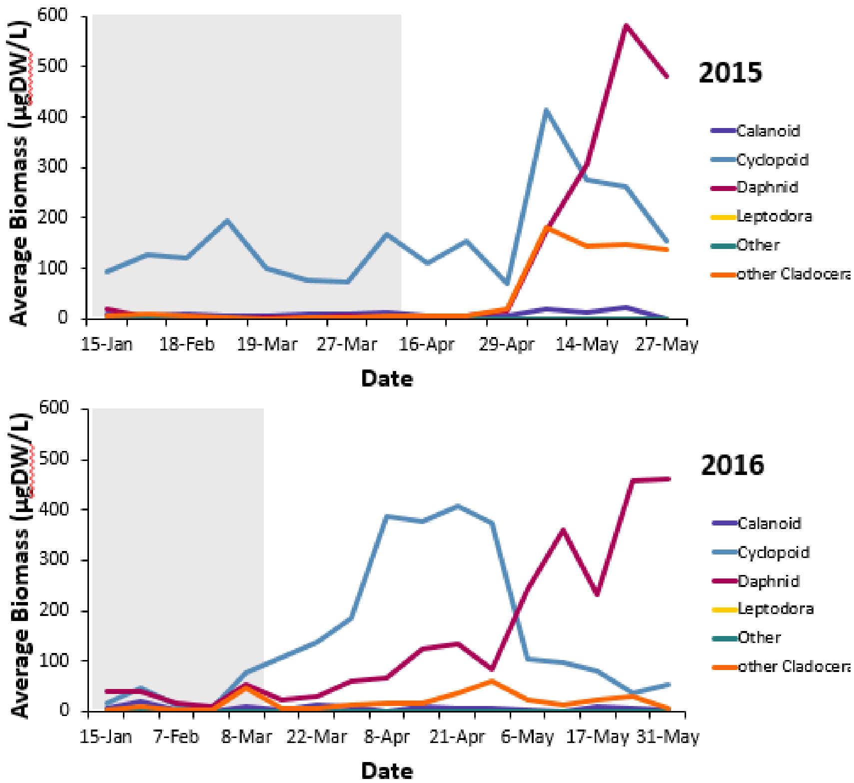

Fig. 5. *Average biomass of zooplankton groups in the spring following a relatively cold winter (2015) and a relatively warm winter (2016). Shaded areas indicate periods of ice cover.*

20. Discussion

Winter limnology has received increased attention in recent years as our knowledge gaps become increasingly apparent[3,4]. As such, the field is rapidly expanding with exciting new results increasing our understanding of winter dynamics[1,12,15]. Other researchers have found that winter is a more dynamic time of year than previously thought, both in terms of physical environment and biological processes. Winter physical conditions may exhibit several distinct phases in large lakes[1], in contrast to simplified inverse stratification models. Our research further suggests that thermal conditions may be vastly different in the same lake depending in winter severity, with a typical inverse stratification pattern for the majority of a cold winter, but isothermal conditions during a warmer winter. This may have implications for phytoplankton communities where different stratification dynamics favor different species[52–54]. Zooplankton communities followed vastly different cycles in a spring following a particularly cold winter versus a particularly warm winter, reinforcing the idea that differences in thermal conditions and duration of ice cover resonated throughout the food web. Other studies have found similar results, where duration of ice cover influenced phytoplankton and zooplankton communities during the early spring[55,56].

Other researchers have performed similar methods to our proposed mesocosm experiments during the ice-free season to understand plankton dynamics in many different scenarios. Previous studies during the growing season examined the effects of increased nutrient inputs[57] and varying grazer species composition[58,59] on phytoplankton communities using suspended mesocosms. For example, mesocosm experiments were used to test the effects of zooplankton grazers on cyanobacteria density[60]. Zooplankton grazers influenced the cyanobacteria concentrations, but specific interactions changed across seasons and fish predation levels. In general, selective herbivores increased cyanobacterial growth when cyanobacteria density was low, but suppressed cyanobacterial growth at high cyanobacteria density[60]. Previous mesocosm studies provide insight into plankton food web interactions and how we may expect cyanobacteria density to respond to zooplankton grazing. However, to our knowledge, mesocosm techniques have not yet been applied to understanding plankton interactions in the context of light limitation under ice. Our preliminary mesocosm tests suggest that high zooplankton grazer densities can influence phytoplankton over the test period of six days, and we would expect the impact to be even higher over a longer incubation period. We predict that differences in light treatments will also vastly alter the phytoplankton community present, as well as overall production. Light is a main driver of phytoplankton production and community structure, especially under ice[13,61], and is expected to be the main driver of phytoplankton communities in our mesocosms. High variability in phytoplankton samples reinforce the importance of sufficient sample sizes for mesocosm experiments.

Our ongoing work on Shelburne Pond has allowed us to build a large database of weekly or bi-weekly field monitoring in conjunction with high-frequency buoy monitoring during the ice-free season that will be instrumental in answering questions about how winter conditions affect ecology throughout the year. We now have three years of continuous data, and a fourth year is in progress for variables including temperature, dissolved oxygen, chlorophyll, phycocyanin, weather variables, nutrients, phytoplankton community composition, and zooplankton community composition. This thorough combination of factors allows in-depth examination of physical differences in lake structure between years and their influence on biota.

20. Training potential.

This funding provided research equipment, travel support, and summer salary for one first-year doctoral student, Allison Hrycik. Allison underwent training in mentoring undergraduate researchers then applied that training to mentor students through UVM undergraduate intern programs and the NSF REU program at the Rubenstein Ecosystem Science Laboratory. Strong mentoring has been linked to enhanced self-efficacy[62–66], persistence in science[67–69], research productivity[70,71], career satisfaction[72,73], and enhanced recruitment of underrepresented minorities[74,75]. Overall, the grant directly funded one graduate student, but enabled mentorship of additional undergraduate students funded through other sources (e.g., NSF REU, UVM Office of Undergraduate Research). One REU student under Allison's guidance, Shannon McFarland, and two UVM undergraduate students, Haley Grigel and Hannah Lister, presented at the Association for the Sciences of Limnology and Oceanography (ASLO) in Honolulu, HI in March 2017. Haley Grigel and Hannah Lister also presented at the University of Vermont's Student Research Consortium in April, 2017.

21. Statement of Government Involvement.

No federal employees collaborated on this project.

22. Information Transfer Plan.

To facilitate broader dissemination of research, we shared our work with the scientific community through conference presentations and journal publications. Two particularly valuable outlets for presentations were meetings of the Association for the Sciences of Limnology and Oceanography (ASLO) and GLEON. GLEON allowed us the opportunity to collaborate with other limnologists studying winter ecology, and Allison is now leading a project that tests the effects of early spring runoff (associated with climate change) on total phytoplankton production during the summer. This is an exceptionally diverse network with whom we are collaborating with Shelburne Pond data as well as Lake Champlain monitoring data not covered in this grant. We also presented our Shelburne Pond work at the ASLO Summer Meeting in June, 2016 in Santa Fe, New Mexico.

Equally important as scientific publications and presentations is sharing research with the public through various outlets. We have integrated our Shelburne Pond sampling into the CREST (Champlain Research Experience for Secondary Teachers) program, a week-long course to expose teachers from grades 7-12 to ecological research and create a plan to incorporate scientific research into their classrooms. Teachers in the program were involved in Shelburne Pond research in the summers of 2015 and 2016, and will be involved in sample collections in summer 2017.

23. Presentations

Grigel, H., Lister, H., Hrycik, A., Lini, A., and Stockwell, J. "Under-ice phytoplankton diel vertical distribution in a shallow hypereutrophic lake." *University of Vermont Student Research Conference*, Burlington, VT, April 2017.

Lister, H., Grigel, H., Hrycik, A., O'Malley, B., and Stockwell, J. "Under-ice diel vertical migration of zooplankton in a shallow hypereutrophic lake." *University of Vermont Student Research Conference*, Burlington, VT, April 2017.

Grigel, H., Lister, H., Hrycik, A., Lini, A., and Stockwell, J. "Under-ice phytoplankton diel vertical distribution in a shallow hypereutrophic lake." *Association for the Sciences of Oceanography and Limnology*, Honolulu, HI, February 2017.

Lister, H., Grigel, H., Hrycik, A., O'Malley, B., and Stockwell, J. "Under-ice diel vertical migration of zooplankton in a shallow hypereutrophic lake." *Association for the Sciences of Oceanography and Limnology*, Honolulu, HI, February 2017.

McFarland, S., Hrycik, A., and Stockwell, J. "The effects of mild versus cold winter conditions on zooplankton community winter-spring transitions." *Association for the Sciences of Oceanography and Limnology*, Honolulu, HI, February 2017.

Hrycik, A. and Stockwell, J. "Lake thermal structure variability under ice between extreme cold and warm winters." *Global Lakes Ecological Observatory Network*, Gaming, Austria, July 2016.

Hrycik, A. and Stockwell, J. "Lake thermal structure variability under ice between extreme cold and warm winters." *American Society for Limnology and Oceanography*, Santa Fe, NM, June 2016.

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24. Investigator's qualifications.

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EDUCATION

University of Vermont, Burlington, Vermont
Ph.D. in Biology: start January 2016, expected completion 2020
Purdue University, West Lafayette, Indiana
M.S. in Fisheries and Aquatic Sciences: expected completion December 2015
Cornell University, Ithaca, New York
B.S. in Natural Resources with Distinction in Research: 2012

RESEARCH EXPERIENCE

Purdue University Department of Forestry and Natural Resources
2013-present: Graduate Teaching and Research Assistant
- Conduct research dealing with diet and movement patterns of Lake Erie yellow perch across multiple environmental gradients
- Examine the effects of hypoxia on aquatic organisms
- Apply both computer modeling and field-based approaches

Cornell University Department of Horticulture
2012-2013: Technician
- Conducted experiments on crop production for the floriculture industry
- Focused on the use of plant hormones as growth regulators

2010-2012: Student Research Assistant
- Assisted researchers and graduate students with various projects

Vermont Cooperative Fish and Wildlife Research Unit
2012, Summer: Technician
- Prepared samples for a study of fish diets using stable isotope analysis

Cornell Biological Field Station
2011, Summer: Honors Thesis Student
- Independent research project on the abundance, bioenergetics, and food web effects of *Mysis* shrimp

2010, Summer: Student Intern
- Assisted research on the effects of introduced fish on zooplankton communities

PUBLICATIONS

Hrycik, A., Almeida, L.Z., and Höök, T.O. Sub-lethal effects on fish provide insight into a biologically-relevant threshold of hypoxia. *In review.*

Hrycik, A., Simonin, P., Rudstam, L., Parrish, D., Pientka, B., and Mihuc, T. *Mysis* zooplanktivory in Lake Champlain: a bioenergetics approach. *Journal of Great Lakes Research* 41(2):492-501.

TEACHING EXPERIENCE

Fisheries Science and Management, Fall 2015—Teaching assistant
Ecology and Systematics of Fishes, Fall 2014—Teaching assistant/Laboratory instructor
Fish Ecology, Spring 2014—Teaching assistant

GRANTS AND AWARDS

Purdue Graduate Student Government Travel Award, May 2015: **$1,000**
NY Chapter of the American Fisheries Society Student Travel Award, February 2011: **$125**

PRESENTATIONS

Hrycik, A., Almeida, L.Z., and Höök, T.O. "Determining an ecologically-relevant definition of hypoxia." International Association for Great Lakes Research, Burlington, VT, May 2015. Oral presentation.

Hrycik, A., Sesterhenn, T., and Höök, T. "An eco-genetic model to understand fish movement decisions." Midwest Fish and Wildlife Conference, Indianapolis, IN, February 2015. Oral presentation.

Hrycik, A., Sesterhenn, T., and Höök, T. "An eco-genetic model to understand fish movement rules." International Association for Great Lakes Research, Hamilton, ON, May 2014. Poster presentation.

Hrycik, A., Simonin, P., Rudstam, L., Pientka, B., and Parrish, D. "Ecology of the opossum shrimp, Mysis diluviana, in Lake Champlain." International Association for Great Lakes Research, Cornwall, ON, Canada, May 2012. Poster presentation.

Hrycik, A., Simonin, P., Rudstam, L., Kraft, C., and Josephson, D. "The effects of introduced rainbow smelt in the Adirondacks." New York Chapter of the American Fisheries Society, Canandaigua, NY, February 2011. Poster presentation.

PROFESSIONAL LEADERSHIP

- Co-chair, "Anthropogenic effects on aquatic food webs" session. *International Association of Great Lakes Research*, Burlington, VT, May 2015. (Co-chaired with L.Z. Almeida and S.A. Ludsin.)
- Vice President, Cornell student sub-section of the American Fisheries Society, 2011-2012.

JASON D. STOCKWELL

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Professional Preparation

B.S. 1991 (Biology, Mathematics) Northland College
Ph.D. 1996 (Zoology) University of Toronto
Postdoctoral Fellow 1996-1997 (Fishery Biology) Colorado State University
Postdoctoral Fellow 1997-1998 (Fisheries and Wildlife) Michigan State University
Fellow 2008 National Conservation Leadership Institute

Appointments

2011-present	Associate Professor of Aquatic Ecology, Rubenstein School of Environment and Natural Resources, University of Vermont
2011-present	Director, Rubenstein Ecosystem Science Laboratory, University of Vermont
2007-2011	Research Scientist, Gulf of Maine Research Institute, Portland, Maine
2003-2007	Field Station Supervisor/Research Fishery Biologist, Great Lakes Science Center, U.S. Geological Survey, Ann Arbor, Michigan
2001-2003	Senior Statistical Analyst, The Jackson Laboratory, Bar Harbor, Maine
1998-2000	Aquatic Biologist III, Massachusetts Division of Marine Fisheries, Gloucester, Massachusetts

Five Related Publications (out of 57 total publications)

Euclide, P.T., and J.D. **Stockwell**. 2015. Effect of gut content on δ^{15}N, δ^{13}C and C:N of experimentally-fed *Mysis diluviana*. *Journal of Great Lakes Research* 41:926-929.

Jones, M.L., B.J. Shuter, Y. Zhao, and J.D. **Stockwell**. 2006. Forecasting effects of climate change on Great Lakes fisheries: models that link habitat supply to population dynamics can help. *Canadian Journal of Fisheries and Aquatic Sciences* 63:457-468.

Stockwell, J.D., P. Dutilleul, and W.G. Sprules. 2002. Spatial structure and the estimation of zooplankton biomass in Lake Erie. *Journal of Great Lakes Research* 28:362-378.

Stockwell, J.D., and O.E. Johannsson. 1997. Temperature-dependent allometric models to estimate zooplankton production in temperate freshwater lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 54:2350-2360.

Sprules, W.G., E.H. Jin, A.W. Herman, and J.D. **Stockwell**. 1998. Calibration of an optical plankton counter for use in freshwater. *Limnology and Oceanography* 43:726-733.

Five Recent Publications

Ball, S.C., T.B. Mihuc, L.W. Myers, and J.D. **Stockwell**. 2015. Ten-fold decline in *Mysis diluviana* in Lake Champlain between 1975 and 2012. *Journal of Great Lakes Research* 41:502-509.

Sierszen, M.E., T.R. Hrabik, J.D. **Stockwell**, A.M. Cotter, J.C. Hoffman, and D.L. Yule. 2014. Depth gradients in food web processes in large lakes: Lake Superior as an exemplar ecosystem. *Freshwater Biology*. DOI: 10.1111/fwb.12415

Yurista, P.M., D.L. Yule, M. Balge, J.D. VanAlstine, J.A. Thompson, A.E. Gamble, T.R. Hrabik, J.R. Kelly, J.D. **Stockwell**, and M.R. Vinson. 2014. A new look at the Lake Superior biomass size-spectrum. *Canadian Journal of Fisheries and Aquatic Sciences* 71:1324-1333.

Stockwell, J.D., D.L. Yule, T.R. Hrabik, M.E. Sierszen, and E.J. Isaac. 2014. Habitat coupling in a large lake system: delivery of an energy subsidy by an offshore planktivore to the nearshore zone of Lake Superior. *Freshwater Biology* 59:1197-1212.

Stockwell, J.D., T.R. Hrabik, O.P. Jensen, D.L. Yule, and M. Balge. 2010. Empirical evaluation of predator-driven diel vertical migration in Lake Superior. *Canadian Journal of Fisheries and Aquatic Sciences* 67:473-485.

Selected Synergistic Activities

- Facilitator, Faculty Development Seminar on Undergraduate STEM Mentoring, 2015.
- Project Co-Leader, "Storm-Blitz: Impact of storms on phytoplankton composition", Theoretical Working Group of GLEON (Global Lakes Ecological Observatory Network)
- Co-Organizer, 2015 Annual Meeting of the International Association of Great Lakes Research, University of Vermont
- PI, NSF Award #1358838**, "**REU Site: Interdisciplinary Research on Human Impacts in the Lake Champlain Ecosystem", 2014-2016
- Manuscript reviewer for Aquatic Ecology, Canadian Journal of Fisheries and Aquatic Sciences, Ecological Applications, Ecology, Fisheries Research, North American Journal of Fish Management, Freshwater Biology, ICES Journal of Marine Science, Journal of Great Lakes Research, Marine Ecology Progress Series, Oecologia, Transactions of the American Fisheries Society, Fisheries Oceanography, and Fisheries and Management Ecology. Grant proposal reviewer for Great Lakes Fishery Trust, Great Lakes Fishery Commission, North Pacific Research Board, Minnesota Sea Grant, and National Fish and Wildlife Foundation.

Graduate Students and Postdoctoral Mentoring

Current: 4 PhD candidates (Trevor Gearhart, Allison Hrycik, Peter Isles, Brian O'Malley), 1 MSc Candidate (Tori Pinheiro, co-advised), 2 MSc committees, 3 PhD committees

Completed (current position): 2 Post-docs (Carrie Byron, University of New England; Emily Nodine, Rollins College), 3 MSc students (E.J. Isaac, Grand Portage Band of Lake Superior Chippewa; Mitchell Jones, PhD Candidate, University of Maine; Peter Euclide, PhD Candidate, University of Vermont), 5 PhD committees, 5 MSc committees

Can early feeding ameliorate thiamine deficiency in wild lake trout fry?

Basic Information

Title:	Can early feeding ameliorate thiamine deficiency in wild lake trout fry?
Project Number:	2016VT83B
Start Date:	3/1/2016
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	Vermont-at-Large
Research Category:	Biological Sciences
Focus Category:	Ecology, Conservation, None
Descriptors:	None
Principal Investigators:	J Ellen Marsden, Carrie L Kozel

Publications

There are no publications.

Title: Can early feeding ameliorate thiamine deficiency in wild lake trout fry?

Statement of Problem: Lake trout (*Salvelinus namaycush*) are native to Lake Champlain but were extirpated in the early 1900s (Ellrott and Marsden 2004). Stocking began in the early 1970s and currently the population is sustained entirely through stocking. Between 39,000 and 271,863 lake trout yearlings are stocked annually in an effort to establish a self-sustaining population (Ellrott and Marsden 2004). Evidence of spawning in Lake Champlain has been found at multiple sites, and eggs and emergent fry have been routinely collected, but little to no recruitment has been documented (Marsden et al. 2005; Riley and Marsden 2009). The causes of this lack of recruitment are not yet understood.

Low recruitment of lake trout in the Great Lakes has been attributed to adult consumption of alewife (*Alosa psuedoharengus*) leading to thiamine deficiency (Brown et al. 2005; Fisher et al. 1996a; Fitzsimons 1995; Honeyfield et al. 2005). Thiamine deficiency complex (TDC) is characterized by a deficiency of thiamine (vitamin B1) that leads to increased mortality in lake trout fry between hatching and the start of exogenous feeding (Brown et al. 2005; Fisher et al. 1996b). Thiamine is a water-soluble vitamin that is essential for carbohydrate and protein metabolism and can only be acquired through the diet (Combs Jr 2012). Symptoms of thiamine deficiency in lake trout include loss of equilibrium, lethargy, whirling, hemorrhaging, and hyper-excitability (Brown et al. 1998; Carvalho et al. 2009; Marcquenski and Brown 1997). Alewife contain thiaminase, an enzyme that breaks down thiamine in the body tissues (Ji and Adelman 1998). As a result, adult lake trout that consume quantities of alewife have insufficient thiamine reserves to allocate to their eggs (Amcoff et al. 1999). To avoid overt mortality, eggs require a minimum concentration of 1.5 nmol/g thiamine, and a concentration of 8 nmol/g egg thiamine is required to reduce secondary effects of thiamine deficiency (Brown et al. 1998; Fitzsimons et al. 2009; Honeyfield et al. 2005). Alewife were found in Lake Champlain in 2003 and rapidly became abundant; they are currently a dominant prey item for lake trout. Based on information from Cayuga Lake and the Great Lakes, hatcheries stocking Lake Champlain began treating culture lake trout fry with thiamine following the invasion of alewife to prevent the occurrence of TDC.

Evidence of TDC in wild fry, the life stage between hatching and yolk-sac absorption, is not well documented because of the challenges of collecting wild fry (Balon 1980; Balon 1976). The majority of information about TDC is derived from hatchery culture settings, where food is withheld from fry until after yolk-sac absorption is complete (Atkins 1905; Leitritz and Lewis 1976). Cultured fry are unresponsive to immobile food pellets during early life stages and do not begin feeding until yolk-sacs are fully absorbed and no internal food source is available. However, wild-hatched fry have access to prey immediately following hatching and experience a period of “mixed feeding” in which they begin exogenous feeding while still using yolk-sac reserves (Balon 1986; Jaroszewska and Dabrowski 2011). Mixed feeding provides an opportunity for fry to mediate mild nutritional deficiencies and could provide lake trout fry with the opportunity to mediate a thiamine deficiency. Previous research found that 20% of fry captured within two weeks of hatching had food in their stomachs, suggesting that wild fry could have access to exogenous nutrients before mortality occurs (Ladago et al. 2015 *in press*). In standard hatchery culture situations, fry are not exposed to food until after TDC has developed but wild lake trout fry may be able to access sufficient thiamine in their diet at early developmental stages and offset thiamine deficiency symptoms

This project will be the basis for a Master's Thesis for a graduate student at the University of Vermont. Research on the potential of early feeding to mitigate thiamine deficiencies in lake trout fry is beneficial to both Lake Champlain and Great Lakes fisheries. Lake trout are one of three top-predators in the Lake Champlain ecosystem, filling an important niche and acting as an indicator of ecosystem health (Edwards et al. 1990) They are also a valuable part of the sport fishery in Lake Champlain, bring in revenue to the surrounding areas (Fisheries Technical Committee 2009). Research will improve the understanding of what is limiting successful restoration in Lake Champlain as well as the Great Lakes. If it is determined that thiamine deficiency is not affecting wild lake trout fry, management tactics can be re-focused on other areas impeding successful restoration.

Statement of Results: The results of this project will be used to improve the understanding of thiamine deficiency affecting early life stages of lake trout and what factors are limiting natural recruitment. This will ultimately lead to improvements in the management of lake trout in Lake Champlain. This information will also be useful for Great Lakes fishery managers and the efforts to improve natural lake trout populations the Great Lakes region.

Objective: Determine if early feeding by wild fry could alleviate thiamine deficiencies and prevent TDC.

Hypothesis: I postulate that wild-hatched lake trout fry can mitigate thiamine deficiency through early feeding on natural prey. The hypotheses are:

1. Fry fed zooplankton will have increased thiamine concentrations relative to unfed fry.
2. Fry fed zooplankton will have increased survivorship relative to unfed fry.
3. The dose-response curve for survivorship as a function of egg thiamine for fry fed zooplankton will shift left relative to that for unfed fry.
4. There exists an egg thiamine level below which feeding fails to compensate for low thiamine levels.

Methods:

Experimental Design

The overall study design will compare thiamine levels in lake trout families with low egg thiamine before and after feeding, and with and without thiamine supplementation of the eggs, relative to initial thiamine levels. This fully crossed experimental design is specifically generated to allow us to determine the effect of early feeding for fry in thiamine replete and thiamine depleted conditions (Figure 1).

Eggs collection and fry rearing

Mature lake trout will be collected in early November 2015, at Gordon Landing, Grand Isle, VT on Lake Champlain. Adult lake trout will be collected by the Vermont Department of Fish and Wildlife as a part of their annual assessment work. Eggs will be collected by manually stripping from 40 ovulating females. A 5g sub-sample of eggs from each female will be put into a Whirl-pak and immediately placed on dry ice, to be sent to SUNY Brockport for egg thiamine analysis. Milt from multiple male lake trout will be collected into 50 mL vials. Lengths and weights of females will be recorded and all fish will be released. Eggs and milt will be kept cool and transported to the Rubenstein Ecosystem Science Laboratory in Burlington, VT for fertilization. Eggs will be fertilized with pooled milt from three male fish and rinsed with dechlorinated water after 5 min. Each egg family will be split in two and kept separate in 10.2 cm diameter polyvinyl chloride (PVC) containers (schedule 40 sewer drain caps), each with a screen bottom and a removable screen top, screen size of 2 mm^2. One group from each family will be placed in a 50 ppm Betadine bath for 1 hour for disinfection. The corresponding group of eggs from each family will be treated with thiamine with an aqueous solution of 5000 ppm thiamine and 50 ppm Betadine for one hour to restore thiamine levels of thiamine-deplete eggs; the thiamine-supplemented eggs are a positive control for the thiamine-deplete eggs. Eggs will be rinsed with dechlorinated water and placed in Heath tray incubators, with flow rates adjusted to 13-15 L/min and the temperature set to 10°C. Incubators will be covered with a black tarp to block light. Temperature will be slowly decreased to 6°C over several weeks to mimic a natural temperature. Eggs will be checked daily until hatching and all dead eggs will be removed. Following the results of the initial thiamine analysis, families will be split in to two groups. Families with initial thiamine concentrations below 4.0 nmol/g will be designated as low and families with thiamine above 4.0 nmol/g will be designated as high. Families with duplicate thiamine levels will be removed.

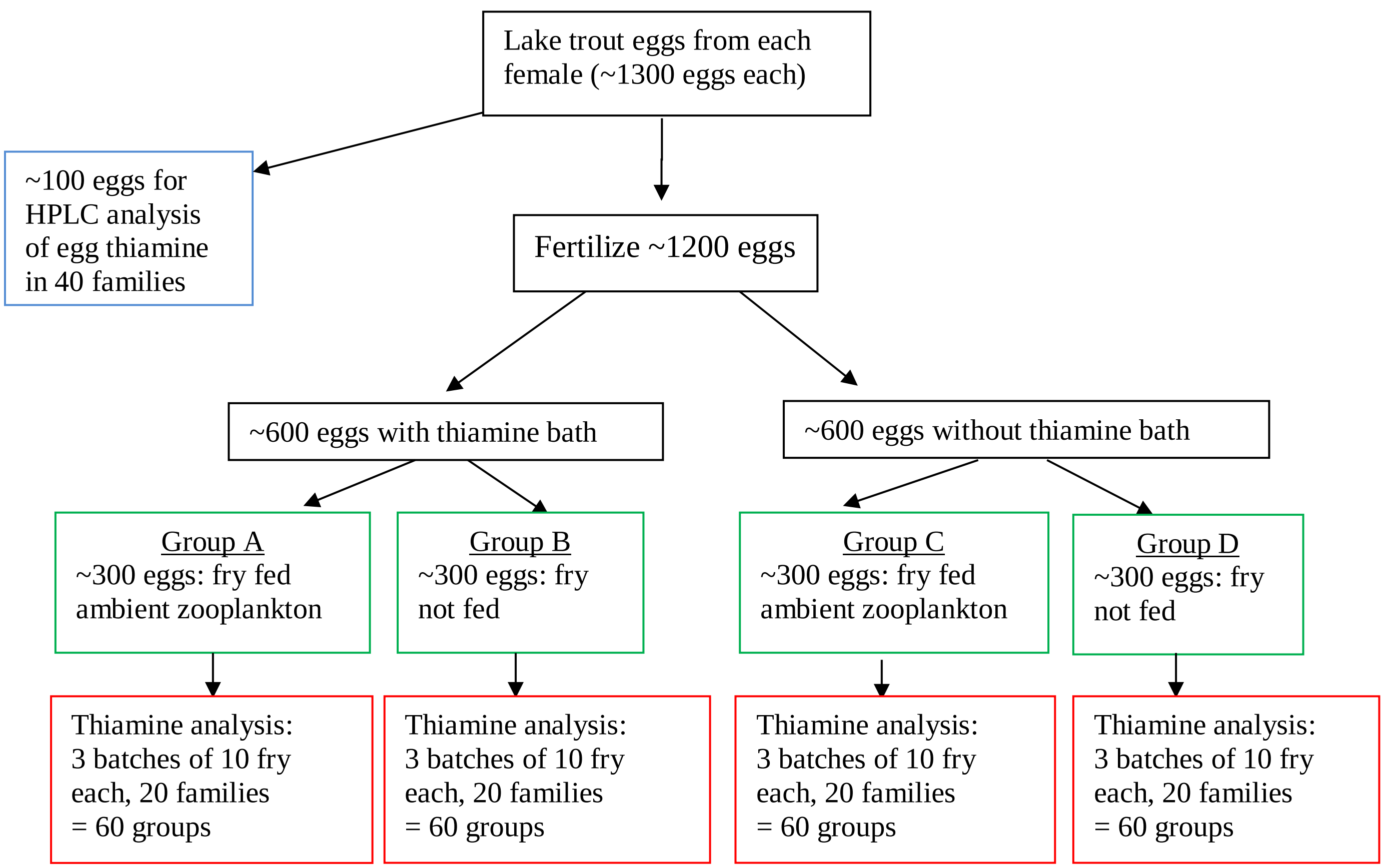

Figure 1. Diagram of experimental design. From funded proposal by J. E. Marsden, J. Rinchard, and A. Evans. Research work commenced in fall of 2014 and will encompass two field seasons with analysis of two year classes of eggs and fry.

Feeding experiments and fry sampling

Six 151 L fish tanks, three replicate tanks for each treatment type, will be set up for feeding experiments at the Rubenstein Laboratory. Tanks will be placed inside a chilled water bath to maintain water temperature at 8° C and filled with clean, dechlorinated water. When at least 50% of the eggs had hatched in a family, 400 fry from the family will be randomly selected, split in half again, and transferred to a 15.2 cm x 12.7 cm x 10.2 cm mesh box constructed of #10 plastic canvas mesh (2.5 mm^2 mesh). One box from each family will be placed in a "fed" treatment tank, the other in the "unfed" tank. The fed group will be given a mixture of zooplankton daily and the unfed group will not be presented with exogenous food. The zooplankton mixture will consist of copepods, rotifers, and *Daphnia sp.* collected from Lake Champlain. The temperature of the tanks will be slowly increased from 8° to 11°C throughout the treatment period to mimic the natural temperatures fry would experience in the wild following hatching. Fry will be sampled weekly and observation of behavior and fitness will be recorded.

Sampling will consist of removing 30 fry from each basket and immersing them in Aqui-S solution until death. Fry will be gently rinsed with DI water, blotted dry, and laid flat in three rows of 10 on a sheet of Glad Press-n-Seal plastic wrap. Samples will be immediately frozen and stored at -80°C until shipment to SUNY Brockport for thiamine analysis. Fry sampled from the fed group will be held for 24 hours without food prior to euthanasia to clear gut contents. This is to ensure that only assimilated thiamine will be measured. Occasionally throughout the study a few fry will be removed from the fed tank and dissected to examine stomach contents to confirm feeding is occurring. The experiment will last until all yolk-sacs are absorbed; remaining alevins will terminated at the end of the experimental period.

Thiamine Analysis

Thiamine analysis will be performed at SUNY Brockport under the direction of Dr. Jacques Rinchard. Individual thiamine vitamers (free thiamine, thiamine monophosphate, and thiamine pyrophosphate) will be extracted from lake trout eggs and fry using 4 mL of trichloracetic acid (2%) and quantified using a high-performance liquid chromatography (HPLC) system as described by Brown et al. (1998). The HPLC system is a Agilent 1200 series which includes a delivery pump, an automatic sample injector, a Hamilton PRP-HI column (150 x 4.1 mm: 5 µm mesh size) with attached guard column, and a fluorometric detector (375-nm excitation wavelength and 433-nm emission wavelength for thiochrome detection). The column thermostat will be set to 30°C. The mobile phase will comprise of 25 mM potassium phosphate buffer (pH 8.4) and N,N-dimethylformamide (DFM). Flow rate will be 1.0 ml/min and the total run time will be 25 min. Eggs will be analyzed in batches of egg family. Fry will be analyzed after removing any remaining yolk to avoid potential interference from maternal nutrient sources. Analyses of each composite fry group will be run twice to evaluate analytical error; if replicates differ from one another more than 20%, the samples will be re-run. If the error is not reduced, the samples will be omitted from the data set.

Data Analysis

1. Fry fed zooplankton will have increased thiamine concentration relative to unfed fry.

I expect to see thiamine concentrations of the fed groups increase throughout the study while the unfed groups decrease. Zooplankton will be a source of thiamine to fed groups but thiamine concentrations of the unfed groups will decrease because of the lack of thiamine input required to maintain metabolic requirements. To test this hypothesis I will calculate the difference in thiamine concentrations between the unfed and the fed fry from each female of the untreated group. If feeding ameliorates thiamine deficiency I expect that the difference will be greater than zero. If the results are normally distributed, a paired t-test will be used to determine if zero is a probable value for this difference. If the results are not normally distributed then a non-parametric sign test will be used to determine whether zero is a probably value. The hypothesis would be supported if zero is not a probable value (left panel of figure 2). The results would refute the hypothesis if zero is a probable value (right panel of Figure 2). The same analysis will be run for the thiamine treated groups. The thiamine levels of the treated fed group will likely remain relatively unchanged because of the metabolic nature of thiamine. Excess thiamine is not stored in the body so a plateau in the thiamine concentrations should be visible in the data. The treated unfed group will have a decrease in thiamine concentrations similar to the untreated group because of the lack of thiamine input.

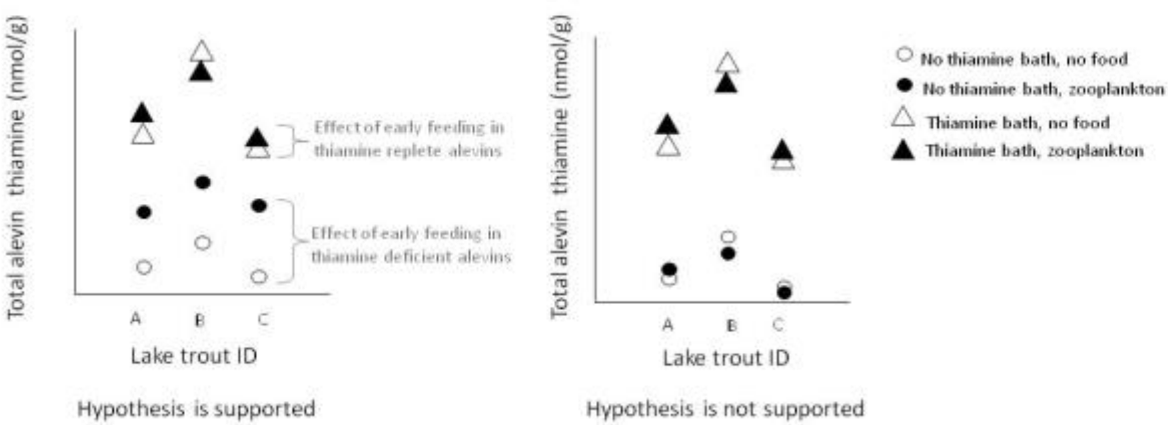

Figure 2. Hypothetical results illustrating findings that would support (left panel) or refute (right panel) the hypothesis that fed fry differ from unfed fry. From funded proposal by J. E. Marsden, J. Rinchard, and A. Evans.

2. Fry fed zooplankton will have increased survivorship relative to unfed fry.

I expect that fry fed zooplankton will have higher survivorship than the unfed fry. To test this hypothesis I will use the same method as the previous hypothesis, calculating the difference in survivorship between the fed and unfed fry of the untreated group for each female over the course of the study. If feeding ameliorates TDC the difference is expected to be greater than zero. Depending on the distribution of fry survival, either a paired t-test or a non-parametric sign test will be used to determine if zero is a probable value for the difference. This process will be repeated with the thiamine treated group.

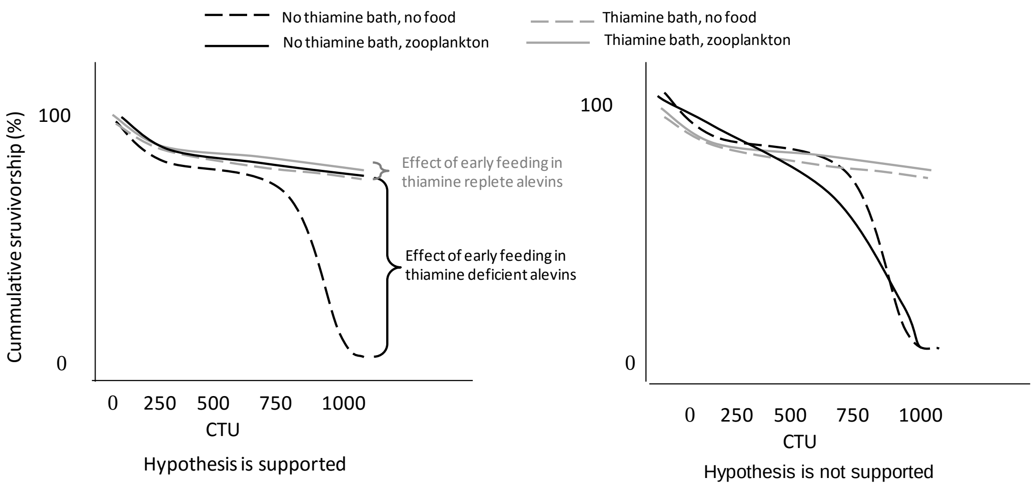

Figure 3. Hypothetical results illustrating findings that would support (left panel) or refute (right panel) the hypothesis that fed fry differ in survivorship with unfed fry. From funded proposal by J. E. Marsden, J. Rinchard, and A. Evans.

3. The dose-response curve for survivorship as a function of egg thiamine for fry fed zooplankton will shift left relative to that for unfed fry.

I expect that the dose-response curve of the fed fry will shift left in comparison to the unfed fry (Figure 4). To test this hypothesis I will determine if there is a difference in the egg thiamine level at which 50% of the fry died (ED_{50}). A dose-response curve of the relationship between survivorship and egg thiamine will be created for each group. The curve for each group will be fit to the points (one for each female) via commonly used modeling methods from toxicity testing literature (Collett 2003, Environment Canada 2005). A logistic regression, probit regression, and non-linear regression will be tested with the curve and final model form will be chosen based on the shape of the dose-response curves. A 95% confidence interval for the ED_{50} will be calculated in an appropriate fashion given the selected model (i.e., Feieller's theorem if logistic regression is used). If the confidence intervals for the ED_{50}s of fed and unfed fry groups overlap, a formal test for their difference will be conducted using an appropriate method, such as the Litchfield-Wilcoxon method or Zajdlik's method (Environment Canada 2005). The same procedure can be used to compare the effect of feeding in thiamine-replete fry.

4. There exists no egg thiamine level below which feeding fails to compensate for low thiamine levels.

I expect that there will be a critical egg thiamine level at which food availability fails to compensate for low thiamine levels. At extremely low egg thiamine levels, overt mortality occurs before feeding begins and critically low thiamine concentrations impact fry behavior and ability to feed. To test this hypothesis I will calculate the difference in thiamine concentrations between the fed and unfed fry of the untreated group. We will test whether there is a change in the magnitude of the difference by using a hockey-stick regression model, which is designed to indicate the value at which the slope of a relationship changes (Figure 5). The same procedure will be used to compare the effect of feeding in thiamine-replete fry.

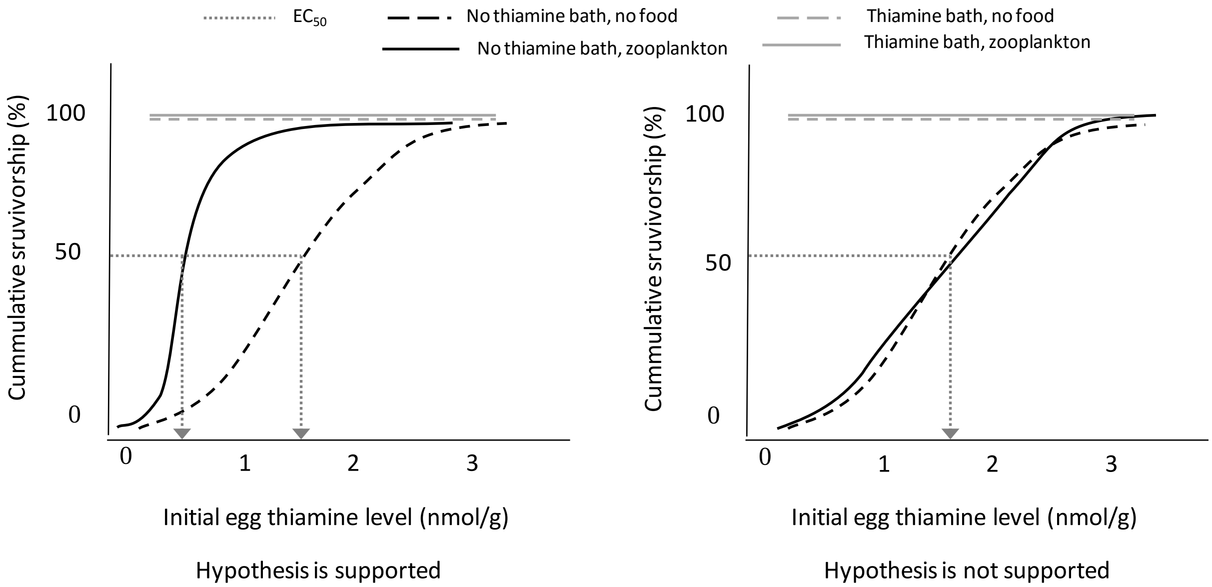

Figure 4. Hypothetical results illustrating findings that would support (left panel) or refute (right panel) the hypothesis that feeding will cause a shift in the survivorship curve. From funded proposal by J. E. Marsden, J. Rinchard, and A. Evans.

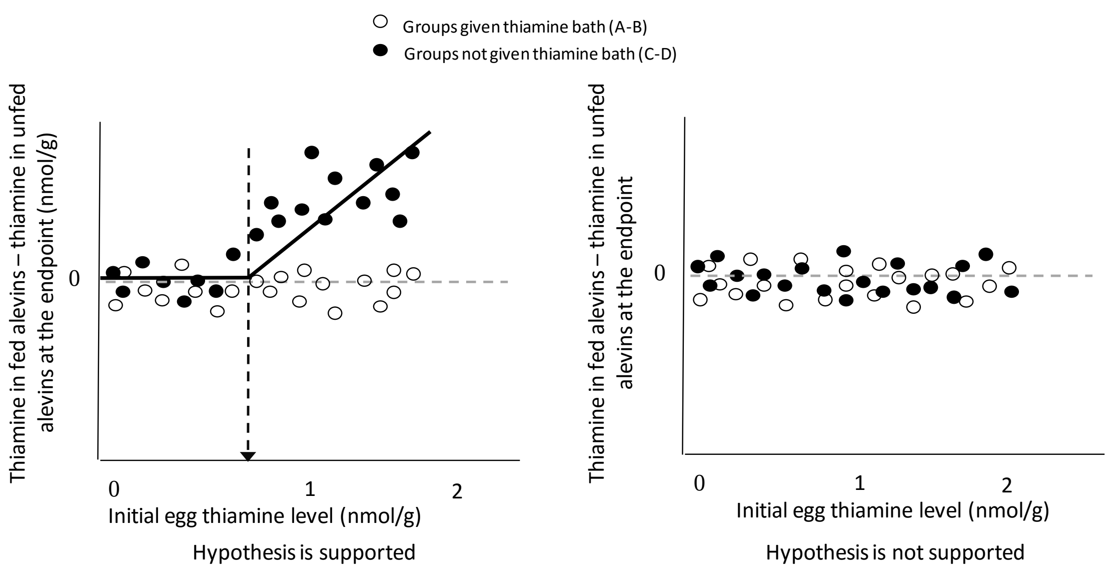

Figure 5. Hypothetical results illustrating findings that would support (left panel) or refute (right panel) the hypothesis that there a critical level of thiamine at which feeding can no longer compensate for thiamine deficiency. From funded proposal by J. E. Marsden, J. Rinchard, and A. Evans.

Findings

Sufficient lake trout eggs for this project could not be obtained in 2015 from Lake Champlain, so we acquired low-thiamine eggs from Cayuga Lake through our colleague on the larger project, Jacques Rinchard at SUNY Brockport. The mean egg thiamine from eggs collected from

Cayuga Lake in 2015 was 10.65 ± 7.02 nmol/g with a range of 1.94 to 28.14 nmol/g. Only three of the twenty families at the egg stage were below the 4 nmol/g threshold that would be expected to show thiamine deficiency signs. There were no significant differences between thiamine concentrations of fry analyzed with and without yolk sacs. Thiamine concentrations of the untreated group in 2015 were not significantly different ($P > 0.05$) between unfed and fed fry. There were no significant differences between the unfed and fed fry of the treated group. There were no significant differences among treatment groups for each of the different thiamine vitamers, thiamine pyrophosphate, thiamine monophosphate, and free thiamine. Overall, mean thiamine concentrations for all treatments in 2015 increased from egg stage to hatching, then decreased to week 6 (Table 2, Figure 4).

In 2015, the mean survival of the unfed and fed fry in the untreated group was 86.5 ± 11.2% and 88.3 ± 8.7% (Figure 5). Mean survival of the fed and unfed fry in the treated group was 84.2 ± 13.6% and 85.5 ± 11.57%. There were no significant differences in survival between unfed and fed fry for either treatment ($P > 0.05$). Several families displayed signs of TDC, specifically lethargy, however, no families in 2015 had high mortality throughout the experiment.

Discussion

The results of this study suggest either that lake trout fry are unable to increase thiamine through feeding on zooplankton or thiamine metabolism is greater than uptake of thiamine through feeding. We hypothesized early feeding by lake trout fry could sufficiently restore thiamine levels to ameliorate thiamine deficiency. We expected low-thiamine, fed fry would show an increase in thiamine concentrations relative to the unfed group of the corresponding families. Thiamine treated families were expected to have sufficient thiamine to fulfill metabolic needs, therefore the effect of feeding on thiamine concentrations would be minimal. In fact, there were no significant differences between any of our comparisons except in 2014, when feeding slightly but significantly *decreased* thiamine levels. A greater difference between mean thiamine was expected for the fed and unfed treatment groups. The differences between means in our experiments were reflected in the TPP vitamer; however, these differences were not biologically significant enough to make a difference in the occurrence of TDC in fry. Feeding was expected to have a greater impact on fry with low thiamine concentrations (< 4.0 nmol/g); however, the fry in our experiments had thiamine concentrations above 4.0 nmol/g at hatching. Thiamine concentrations of fry decreased throughout the post-hatch period but never fell below 4.0 nmol/g. Thiamine is water soluble and excess thiamine is not stored in the body, therefore when thiamine concentrations in fry were above the metabolic requirements, thiamine concentrations would not be expected to change due to feeding. Consequently, the fry we used may not have had sufficiently low thiamine to detect the effect of feeding on thiamine levels.

Our results do not support our second hypothesis that survivorship would be higher in families fed zooplankton. We expected that survival would be higher in untreated, fed families relative to untreated, unfed families and we expected survival to be higher in thiamine-treated families relative to the untreated families. Overall, survivorship did not differ among treatments. High survival of all families could be related to high thiamine levels at hatching and throughout the experiment.

Increases in thiamine concentrations from fertilization to hatching in the untreated fry were unanticipated. The treated group was expected to increase thiamine from egg to hatching because they received a thiamine treatment during fertilization, whereas thiamine concentrations were expected to decrease in the untreated group during egg development to hatching. Little information is available on the metabolism of thiamine in lake trout eggs and the few studies that have focused on eggs did not measure thiamine from egg stage to hatching, usually measuring thiamine later in development when TDC signs and mortality occur. Thiamine is assumed to decrease throughout development as maternal sources of thiamine are used for energy metabolism. The increases in thiamine from egg to hatching in both years suggest that there was an exogenous source of thiamine that lake trout eggs were able to absorb. Possible causes of the thiamine increase from egg stage to hatching include contamination, analytical errors, thiamine production by bacteria, differential mortality of eggs dependent on thiamine levels, and absorption of available thiamine from the water in which eggs were reared in.

Contamination and analytical errors can be eliminated as possible causes for the increase in thiamine. In 2015 treatment groups were completely isolated from each other and kept on separate water sources throughout rearing. Analytical errors could have occurred during thiamine analysis but would have been detected, as replicate samples were run at each time point for each family measured. If replicates had >20% difference in thiamine the samples were re-run and any samples still with >20% difference were eliminated from the analysis.

Bacteria in the intestinal tract of humans are known to synthesize thiamine that can be absorbed by the gut for use (Burkholder and McVeigh 1942; Aruguman et al. 2011; Nabokina et al. 2014). Bacteria could have become established in the lake trout embryos and synthesized thiamine that was available for uptake, though this has not been studied in lake trout. Lake trout eggs were disinfected with a betadine solution during water hardening, but this process may not eliminate all bacteria (USFWS 2004). Water used for rearing was de-chlorinated water from the Burlington Water Treatment Facility; standard water treatment should eliminate any living bacteria in the water. Thus, bacterial contamination does not appear to be a likely source of thiamine in eggs.

If thiamine concentrations vary substantially among eggs from a single female, high mortality during the egg stage could have led to skewed results from the feeding experiment. Egg thiamine measurements were performed on a random subsample from each family and represent an average, but the variance among individual eggs is unknown. If eggs with low thiamine levels died during embryonic development, only those with high thiamine concentrations would survive to hatching and be available for analysis. Similarly, if fry with high thiamine were more likely to survive, sampled fry would represent a biased sample; we could not measure the thiamine of dead fry. However, no groups showed high mortality at either the egg or fry stages, and the families with slightly higher mortality relative to others did not correspond with any of the families with low egg thiamine.

Alternatively, eggs could have obtained thiamine from exogenous sources during development, i.e., from the water in which they were reared. Thiamine is absorbed through the chorion, as evidenced by the use of thiamine baths to treat lake trout eggs to prevent TDC (Wooster et al. 2000; Brown et al. 2005). Thiamine is naturally present in water in the environment; however, very little is known about differences in thiamine concentrations across water bodies (Hutchinson 1943, Kurata and Kadota 1981). Plants and bacteria in water synthesize thiamine; during decomposition they could leach thiamine into the water column (Bender 1999). Thiamine may also be available from excretion by fishes and other vertebrates (Manzetti et al. 2014).

However, whether natural thiamine is retained in water after standard water treatment is not known; analytical methods for measuring low concentrations of thiamine in water have not yet been fully developed. Thus, the source of water for rearing lake trout eggs could be a significant variable that affects exposure to thiamine.

Hypothetically, different water sources could affect thiamine concentrations in lake trout eggs. Eggs raised in different hatcheries with different water sources do show varying occurrences of EMS/TDC (personal comm. Dale Honeyfield/Jacques Rinchard). Many hatcheries rear fry in well water while others draw water from streams or the hypolimnion of nearby lakes. Photosynthetic productivity is absent in well water, but the presence of thiamine-synthesizing bacteria in well water is unknown. In contrast, algae, bacteria, and plants in lake water produce natural thiamine which is available to fry. In our experiments, eggs and fry from Cayuga Lake reared in Burlington, VT had different survival from eggs and fry from the same Cayuga Lake parents reared in Brockport, NY (personal comm. Jacques Rinchard). But, both laboratories use treated city water that is drawn from nearby lakes, so the cause of the difference in thiamine concentrations and survival is unclear.

Lake trout eggs and fry adsorb sufficient thiamine for metabolic use when exposed to high-concentration thiamine baths, but the concentrations of thiamine in lake water are generally very low (Hutchinson 1943, Kurata and Kadota 1981). However, lake trout eggs incubate for up to six months in the wild, which may allow adsorption of sufficient thiamine even at very low concentrations. Theoretically, the amount of thiamine absorbed by the egg could be calculated if the concentration of thiamine in the water, the rate of diffusion, and the total incubation time are known. Based on laboratory and hatchery practices, we know that incubating eggs in a thiamine bath of a specific concentration for a set amount of time results in an elevated egg thiamine concentration. To calculate the thiamine uptake at a much lower concentration we need to assume 1) there is a constant uptake of thiamine and 2) the relationship between uptake of thiamine and thiamine concentration in the environment is linear. Empirical data on thiamine concentrations in eggs incubated for long periods at very low thiamine concentrations would be highly useful.

Thiamine deficiency in hatchery-reared lake trout has been extrapolated to the wild and has been frequently suggested as a cause for lake trout recruitment failure in the Great Lakes (Fisher et al. 1996; Marcquenski and Brown 1997; Brown et al. 2005; Muir et al. 2012). In Lake Huron, for example, recruitment of wild lake trout began to appear after alewife populations crashed in the 1990s (Riley et al. 2007). In Lake Champlain, similar to the Great Lakes, lake trout egg thiamine concentrations decreased following the invasion of alewife in the early 2000s, from a pre-alewife concentration of 11.1 nmol/g to a low of 2.9 nmol/g in 2009 (Ladago et al. in review). In contrast to the Great Lakes, however, the first evidence of sustained natural recruitment of lake trout was seen beginning in 2015, *after* alewife arrived (unpublished data) and despite low egg thiamine concentrations. Recruitment is the result of high survival of wild fry, and supports our initial hypothesis that thiamine is in some way mitigated during development in the wild. Our experiments do not rule out a role of feeding in thiamine acquisition, but add the possibility that thiamine may be adsorbed from water.

Training potential

This project provided additional funding for Carrie Kozel's Master's degree research at the University of Vermont with Dr. Ellen Marsden. Two undergraduate students at the University of Vermont received training as a part of this project.

Presentations

Kozel, C.L. Early feeding in lake trout fry and thiamine deficiency. 2016. University of Vermont, Burlington, VT. Thesis Defense.

Kozel, C. L., J. Rinchard, A. Evans, and J. E. Marsden. 2017. Early Feeding in Lake Trout Fry as a Mechanism to Ameliorate Thiamine Deficiency. International Association of Great Lakes Research annual conference, Detroit.

Theses

Kozel, C. L. 2016. Early Feeding in Lake Trout Fry (*Salvelinus Namaycush*) as a Mechanism for Ameliorating Thiamine Deficiency Complex. Master's Thesis, University of Vermont, Burlington VT

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J. ELLEN MARSDEN

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RESEARCH INTERESTS

Great Lakes fisheries restoration and ecology; ecological effects of introduced species; lake trout early life history and spawning behavior; conservation of genetic resources in fisheries

EDUCATION

Ph.D. - Cornell University, Department of Natural Resources, 1988.
M.S. - Cornell University, Ecology & Systematics, 1985.
B.A. - Bryn Mawr College, Biology, 1978.

PROFESSIONAL EXPERIENCE

Professor, University of Vermont, since 2006; Chair, Wildlife and Fisheries Biology Program, 2012-2015

Associate Professor, University of Vermont, 2001 – 2006; Assistant Professor, 1996 - 2001

Associate Professional Scientist, Illinois Natural History Survey; Director, Lake Michigan Biological Station, 1990-96

RECENT GRANTS

2016 Kozel, C., and J. E. Marsden. Can early feeding ameliorate thiamine deficiency in wild lake trout fry? Water Resources Center – thiamine and fry - $10,000

2015 Marsden, J. E. Evaluation of successful lake trout recruitment in Lake Champlain: what has changed? UVM John Hilton faculty research fund, $10,151

2014 Marsden, J. E. and J. D. Stockwell. An acoustic telemetry array for Lake Champlain: investigating effects of aquatic habitat fragmentation on lake whitefish. Water Resources Center. $40,000

2014-2015 Marsden, J. E., J. Rinchard, and A. Evans. Can early feeding in lake trout fry ameliorate thiamine deficiency? Great lakes Fishery Commission. $138,977

2013-2018. Marsden, J. E. and J. D. Stockwell. Lake Champlain fish ecology: a mesocosm approach to the Great Lakes. Great Lakes Fishery Commission. $945,000.

2013-2014. Marsden, J. E., C. Guy, R. Gresswell. Evaluation of lake trout egg distribution, density, and survival in Yellowstone Lake. Wyoming Council of Trout Unlimited. $190,000

2012-2013 Marsden, J. E., J. Johnson . Attraction of spawning lake trout to conspecifics and reef odor. Great Lakes Fishery Commission $50,000

2011-2013. Marsden, J. E., W. Kilpatrick, and W. Ardren. Genetic examination of lake whitefish population sub-structuring among basins in Lake Champlain. State Wildlife Incentives Grant, VTDFW, $39,688

SELECTED PROFESSIONAL ACTIVITIES

Board of Technical Experts, Fisheries Research Board of the Great Lakes Fishery Commission, 2014 - present

Sea Lamprey Research Board, Great Lakes Fishery Commission, 2003-2012 (Chair 2005 – 2010)

Lake Champlain Basin Program Aquatic Nuisance Species Committee, 2005 - present

Lake Champlain Fisheries Technical Committee, 1997 - present

RECENT PUBLICATIONS

REVIEWED CHAPTERS

Marsden, J. E., P. Stangel, A Shambaugh. 2013. Zebra mussels in Lake Champlain: a sixteen-year monitoring database. Chapter 2, In: T. Nalepa and D. Schloesser, Quagga and Zebra Mussels: Biology, Impacts, and Control, 2nd ed. CRC Press.

Thurow, R. F., C. A. Dolloff, and **J. E. Marsden**. 2012**.** Visual observation of fish and aquatic habitat. Chapter 17, In: A. V. Zale, D. L. Parrish, and T. M .Sutton, eds., Fisheries Techniques 3rd ed., American Fisheries Society, Bethesda, MD.

REVIEWED JOURNAL ARTICLES (* indicates graduate student authors; ** undergraduate student authors)

Johnson, N. S, D. Higgs, T. R. Binder, **J. E. Marsden**, T. Buchinger, L. Brege, T. Bruning, S. Farha and C. C. Krueger. In press. Evidence of sound production by spawning lake trout (*Salvelinus namaycush*) in lakes Huron and Champlain. Can. J. Fish. Aquat. Sci.

Binder, T. R., J**. E. Marsden**, S. C. Riley, J. E. Johnson, N. S. Johnson, J. He, M. Ebener, C. M. Holbrook, R. A. Bergstedt, C. R. Bronte, T. A. Hayden, and C. C. Krueger. In press. Lake-wide movements and spatial segregation of two populations of lake trout, *Salvelinus namaycush*, in Lake Huron. J. Great Lakes Res.

Pinheiro*, V. M., J. D. Stockwell, and **J. E. Marsden**. 2016. Lake trout (*Salvelnus namycush*) spawing site use in Lake Champlain. J. Great Lakes Res. 00:00-00

Marsden, J. E., J. Johnson, J. He, N. Dingledine, J. Adams, T. R. Binder, N. Johnson and C. C. Krueger. 2016. Five-year evaluation of habitat remediation in Thunder Bay, Lake Huron: comparison of characteristics of constructed reefs that attract spawning lake trout. Fisheries Research 183:275–286

Ladago*, B. J., **J. E. Marsden**, and A. Evans. 2016. Could early feeding by lake trout fry mitigate thiamine deficiency? Trans. Am. Fish. Soc. 145:1-6

Marsden, J. E., H. Tobi**. 2014. Sculpin predation on lake trout eggs in interstices: skull compression as a novel foraging mechanism. Copeia. 2014:654-658 (received award for Best Paper of 2014)

Lochet, A, B. J. Fryer , S. A. Ludsin, E. A. Howe, and **J. E. Marsden**. 2014. Discriminating the natal origin of spawning adult sea lamprey (*Petromyzon marinus*): reevaluation of the statolith microchemistry approach. N. Am. J. Fish. Manage. 40:763-770.

Janssen, J., **J. E. Marsden**, T. R. Hrabik, and J. D. Stockwell. 2014. Are the Laurentian Great Lakes great enough for Hjort? ICES Journal of Marine Science. 71:2242-2252

Lochet, A., **J. E. Marsden**, B. J. Fryer and S. A. Ludsin. 2013. Instability of statolith elemental signatures revealed in newly-metamorphosed sea lamprey (*Petromyzon marinus*). Can. J. Fish. Aquat Sci 70: 565-573

Herbst*, S. J., **J. E. Marsden**, and B. J. Lantry. 2013. Lake whitefish diet, condition, and energy density in Lake Champlain and the lower four Great Lakes following dreissenid invasions. Trans. Am. Fish. Soc. 142:388-398

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Personal Statement
My goal is to be a part of a group passionate about and dedicated to the preservation of the Great Lakes and other freshwater systems through the research of ecology, behavior, hydrology, and human interactions.

Education
University of Vermont (2014-Present)
M.S. Candidate RSENR Aquatic Ecology

Michigan State University (2009-2013)
B.S. in Fisheries & Wildlife
Concentrations in Fisheries Management and Water Sciences

Awards
Rebecca Humphries Undergraduate Scholarship 2013; *Michigan Charter Boat Association Undergraduate Scholarship* 2012; Dean's List Fall 2011, Spring 2012; *Most Active Member Award* 2011 MSU Fisheries & Wildlife Club

Experience

8/2014-Present — **Graduate Student Research Assistant, University of Vermont, Burlington, VT. Dr. J. Ellen Marsden**

- Thesis: Can early feeding in lake trout fry ameliorate thiamine deficiency?

4/2014-8/2014
1/2013-8/2013
5/2012-7/2012 — **Sea Lamprey Research Technician, Hammond Bay Biological Station, Millersburg, MI. Jason Bals, Thomas Luhring, Dr. Michael Wagner**

- Assisted in the investigation of alarm cue response of sea lamprey in both mesocosm and field experiments using a PIT System. Mesocosm experiments were conducted in a man-made stream at Hammond Bay Biological Station and field experiments were done on Carp River near Wilderness State Park, MI.
- Assisted with acoustic tagging on Lake Huron with Trevor Meckley.

8/2013-12/2013 — **Lake Trout Research Technician, Hammond Bay Biological Station, Millersburg, MI. Tyler Buchinger, Nicholas Johnson, Dr. Weiming Li**

- Assisted in the investigation of lake trout pheromones used for spawning in mesocosm experiments using a PIT system.

3/2011-5/2012 **Lab technician, Limnology Laboratory**

Natural Resources Building, Michigan State University. Dr. Orlando Sarnelle

- Investigated the functional feeding response of zebra mussels at low food concentrations.
- Assisted graduate student Jeff White in the investigation of *microsystis* toxicity and zebra mussel mortality.

Publications

Sarnelle, O., J.D. White, T.E. Geelhoed, **C.L. Kozel**. 2015. Type III functional response in the zebra mussel, *Dreissena polymorpha*. Canadian Journal of Fisheries and Aquatic Sciences. 72:1202-1207.

References

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Information Transfer Program Introduction

The Vermont Water Resources and Lake Studies Center facilitates information transfer in a variety of ways. The Director, Dr. Breck Bowden, and Program Coordinator, Elissa Schuett, participate in committees and meetings as representatives of the Vermont Water Center. Dr. Bowden is a member of the Technical Advisory Committee and Steering Committee for the Lake Champlain Basin Program, sharing work being funded by the Vermont Water Center with others in the region. He also is actively involved in the “Common Circle” steering committee and the “Solutions” team for the Network for Clean Water, a program being led by the ECHO, Leahy Center for Lake Champlain to address water quality issues in the region. Ms. Schuett attended the annual meeting of the Vermont Monitoring Cooperative and shared information about the Vermont Water Center during a poster presentation.

The Center maintains several websites, including the Vermont Water Resources and Lake Studies site that highlights emerging research funded by the Center or relevant to water resources management in Vermont. A regional network website was developed for the New England Regional Water Resources and Research Centers. The website is updated with news relevant to regional water resources issues, RFP announcements, and links to each of the Water Resources Research Institutes and the Water Science Centers in the New England region (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont).

Support by the Water Center of the e-digest publication, ecoNEWS VT (http://www.econewsvt.org/), continued in 2016, highlighting water resources and aquatic ecological research from across Vermont, including research funded by the Vermont Water Center. Research digests are derived from peer-reviewed reports and articles and distilled into short articles for a non-expert audience. All digests are archived on the website as a resource for managers, lawmakers, and researchers. Quarterly emails are sent to approximately 300 subscribers with featured articles and information. Three email issues with 14 new stories were produced in 2016, including several articles about Water Center funded projects. The publication is a collaboration with several other organizations, including Lake Champlain Sea Grant, Northeastern States Research Cooperative, and Vermont Monitoring Cooperative.

In addition to the e-digest issues, all articles are archived online and tagged for cross-reference of similar topics. A section of the website is used to capture ecological research being conducted outside Vermont, but relevant to issues found in Vermont. Events are also maintained on the website to inform visitors about seminars, public meetings, and workshops. Social media is also used to alert followers to recent digests and relevant ecological research news.

Elissa Schuett manages the communications and information transfer for the Water Center. Ms. Schuett also coordinates communications for Lake Champlain Sea Grant, bringing knowledge from the Sea Grant network and being able to broaden the reach of the information transfer from the Water Center. A graduate student was supported part-time by the Water Center to assist Ms. Schuett with writing feature stories and management of the outreach efforts of ecoNEWS VT.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	0	0	0	0
Masters	1	0	0	0	1
Ph.D.	4	0	0	0	4
Post-Doc.	0	0	0	0	0
Total	5	0	0	0	5

Notable Awards and Achievements